Soil water studies in a hillslope segment of an upland catchment in south east Scotland

by

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PhD

University of Edinburgh

1986

Declaration

This thesis has been composed by myself and it has not been submited in any previous application for a degree. The work reported within was executed by myself unless otherwise stated.

To

Mario, Gabriel and Pedro.

Acknowledgements

I would like to express sincere gratitude to my supervisors Dr. Peter A. Furley and Dr. Derek B. Naysmith for their guidance and encouragement throughout this work. I am also grateful to Dr. David C. Ledger for his useful comments

I am also indebted to Robert Howard and Ian Crichton for their help in the field work in Boghall Farm.

Lastly, I would like to thank the Brazilian government for awarding the scholarship for this study.

Abstract

This study describes the basic types and temporal patterns of soil water flow, over a hillslope segment of an upland catchment in south east Scotland. The soil of the hillslope segment studied belongs to the group classified as freely drained brown earths, and is covered by improved grassland used as a pasture. Lateral water flows were collected by means of insertion of plastic gutters into the soil profile at three small replicated plots, isolated from the surrounding soil by cemented water-tight boundaries, together with one further reference plot lacking artificial boundaries. The plots were adjacent to each other and similar in terms of soil parent material, angle of slope, vegetation cover and general soil properties.

The three plot replicates were designed to give reasonable predictions concerning the runoff events over the hillslope segment studied. The temporal patterns of flows between plots were similar and no significant differences, between the replicates, in terms of runoff events or amounts, were detected by the end of the period of observation. The pattern of events was reasonably

explained using a simple model relating runoff to rainfall alone. Regression models demonstrated that between 20 and 50% of the runoff events can be directly related to rainfall.

Soil water balance studies indicated that runoff quantities were low over the eighteen months of observation, and that most of the runoff events occurred when the soil was under moisture deficit. High runoff quantities were, infrequently, related to extreme rainfall episodes, indicating that in these circumstances Horton overland flow may occur over the hillslope. As the soil water was replenished, during the wet periods, vertical flows down the soil profile prevailed over lateral flows. This behaviour of the soil water flow has provided the evidence for the suggestion that matric potential gradients within the soil profile form one of the main controlling factor for runoff generation. It is also suggested that the apportionment of the water flow over the hillslope segment studied cannot be satisfactorily explained by Hewlett's or Horton's runoff models. The nearest approximation to the flow regime in the soil profiles studied here, is given by Burns' model for predicting the movement of water and salts in freely drained soils.

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Chapter One

Introduction

Investigations of hydrological processes date from the 1930s, mainly through the work of Horton and data provided by the use of plots and research watersheds after the establishment of the U.S. Soil Conservation Service in the late 1930s.

The work of Horton resulted in a model to predict runoff based on the infiltration capacity of the soil, which declines with time after the onset of rainfall, reaching a fairly constant rate after one-half to two hours into the storm. If during the storm, rainfall exceeds infiltration capacity, the water accumulates in the soil and fills small depressions (depression storage). If subsequently, the depression storage is exhausted, water spills over and runs downslope as an irregular sheet called overland flow. This work on plots and watersheds provided much valuable information on the effects of land treatment and soil physical characteristics on amounts and rates of runoff. The development of the universal soil-loss equation is an outstanding example of what can be achieved with the data from these areas (Amermann and McGuiness, 1967).

Until the 1960s, the major application of hydrology was for reservoir design and flood forecasting. The background of hydrology in this period rested on the effectiveness of a few concepts, especially the infiltration theory of surface runoff, and the unit hydrograph model (Sherman, 1932) for forecasting the timing of river discharge following rainfall. Streamflow forecasting based on these ideas, was entirely adequate for large natural catchments and small impermeable areas, but less efficacious for small headwater areas (Kirkby, 1978).

Since 1960, increasing concern over water resources has focused attention on how little is known about the source of high-quality surface water from upland catchments. Classical explanations, concerning the source of non-storm streamflow (baseflow) and stormflow, were contradicted by the results obtained at the Coweeta Hydrological Laboratory in the Southern Appalachians of western North Carolina. It was found that on steep, forested slopes, with narrow incised streams and moderately deep soil, storms produce little or no overland flow. Furthermore, ground water wells failed to demonstrate saturated aquifers except along streams and drainage ways, where water emerges as spring or seepage flow (Hewlett and Hibbert, 1963). The conclusions from this, and subsequent studies, showed that under humid climates, baseflow is provided by water stored in the soil mantle and that most stormflow is supplied by subsurface flows. Both baseflow and stormflow source areas are subjected to expansion or shrinking depending on the amount and duration of rainfall.

The work of Hewlett (1961) and Hewlett and Hibbert (1967) resulted in models (variable source area models) which are concerned with subsurface water movements (rather than infiltration rates). These are now accepted to represent tha actual pathways, residence times and sources of water as it flows through headwater streams. Horton's runoff model now has its application restricted to impermeable areas or locations which have been disturbed by man.

Studying the flow components of a hillside, Kirkby (1969), confirmed that subsurface flow is a probable dominant mode of hillslope flow in humid and humid-temperate areas. He also pointed out that in semi-arid areas, surface flow (Horton's overland flow), is the dominant process whenever rainfall intensity exceeds the soil infiltration rate. He further concluded that, in suitable conditions, both surface and subsurface flows can occur at any point in a catchmnent although their relative frequency can vary from point to point. From this study, Kirkby proposed a simple model to explain the production of subsurface flow discharge over hillslopes. However, although models such as Hewletts' and Hortons' find widespread application in a variety of areas, there are few formal experiments designed to verify their structure and their suitability for other areas. For example, in humidtropical areas, it appears that many types of flows (surface, subsurface runoff, runoff on saturated soil with groundwater rising to the surface) occur at the same catchment (Dubreuil, 1985). Also, results of experiments carried out in humid-temperate areas, give rise to doubt about the use of Hewlett's model to explain the disposition of water over an upland catchment (Baloutsos, 1985). Referring to Kirkby's models, although a number of studies might be said to provide a general comment on these theories and in the models that have been generated, none of them have adopted a sufficiently rigorous approach for their verification or to the way in which they have been developed (Burt and Walling, 1984). This is evident in the lack of replication, hence the absence of satisfactory statistical verification and in the error checking of the methods employed.

In addition to the problem of scarcity of formal experiments to investigate the models, there exists the problem of representativeness of the data. Difficulties arise due to the frequent omission of a large enough sample sizes to predict accurately the numerical characteristics of a given variable; frequently a single storm event, soil sample or laboratory measurements is used to support major conclusions (Burt and Walling, op.cit). On a similar note, Freeze (1978), has also pointed out that the scarcity of representative data imposes serious limitations on the mathematical modelling of hillslope processes.

In the context of the United Kingdon, a considerable amount of information on hillslope flow processes and natural source areas for streamflow has been generated, especially from the studies conducted by the Institute of Hydrology at Plynlimon in Mid-Wales (Institute of Hydrology, 1978). Results emerging from such experiments already permit the recognition of Hewlett's variable source area and subsurface flow concepts as a relevant model to explain streamflow generation in Britain. However, when considering the expansion of these concepts to other areas of the country such as southeast Scotland, it becomes apparent that available information is still insuficient to predict with confidence the behaviour of water flows over hillslopes.

The work reported in this thesis is prompted by this need for further detailed information about runoff processes over hillslopes, including an assessment of the accuracy of the results. Installation of the study site was carried out in a small catchment at Boghall farm, in southeast Scotland. The site was selected because of its proximity to Edinburgh, the fact that it would provide useful information about the behaviour of the soil water in a well drained site and also because it was owned and operated by the Department of Agriculture of the University.

The experiment consisted of repeated measurements of rainfall, runoff, soil water potential and soil water content from replicated raingauges, small plots, tensiometers and neutron probe acess tubes. Replication was an essential characteristic in design of the experiment, since the main objective of the experiment was to extend the available information on hillslope flow processes, considering variation and improvement in the precision of the results. It was hoped that consideration of the nature and magnitude of the errors in such experiment would help to resolve criticisms concerning previous work using confined plots and enable more accurate comparisons between experiments to be made.

Initially, the proposed study was planned to instrument four experimental sites each having three replicated plots within the catchment. The intention was to compare the effect of contemporary land use on the soil water regime of two opposing hillslopes, one covered with heather-moorland vegetation and the other with improved grassland, and both currently utilized as a pasture. The first study site was installed in the mid slope of the south facing valley side, covered with improved grassland. However, difficulties related to the construction of the site (removal of considerable amount of soil to construct the artificial plots and transport of heavy materials upslope), the measurement of a considerable amount of data, and an additional delay in obtaining permission to work in the heather-moorland area, (which belongs to the Ministry of Defence) limited the experiment to one site. Therefore, in view of these problems, efforts were concentrated in the identification and definition of basic flow processes and their variability in time by means of a controlled experiment at one site covered by improved grassland. Information provided by such a limited study would still provide useful information in view of the earlier comments on the lack of experiments dealing with flow processes in hillslopes of southeast Scotland. In addition, as will be outlined later, the approach adopted allowed for consideration of the quality of the data by assessing the measurements errors, an aspect mostly neglected in this type of research.

The structure of the project is set out below within six chapters. Chapter two presents a bibliographical review assessing the literature relevant to the project. This chapter considers the flows over the surface of the soil, the fundamentals of soil water potential and the soil water balance.

Chapter three describes the physical characteristics of the study site. Initially a regional description of the geology, land forms, climate and soils is presented, leading to a more detailed examination of the physical features and particularly the soil and vegetation of the actual study area.

Chapter four describes the methods used in the experiment. It reports on the instrumentation of the site and the problems eencountered in making routine measurements, treating the results and establishing data accuracy.

Chapter five outlines and discusses the results. At first a broad picture of the results is presented, then this is followed by an analysis of the weekly water balance separated for the dry and wet period of 1984 field season. The second field season, 1985, was analysed as one single period.

Finally, chapter six reports the conclusions that can be drawn from this project.

Chapter Two

Selected literature review

This chapter presents a selected review of the relevant literature used to develop and set up this project. The chapter is divided into four sections.

2.1 Flows of water over the soil surface

2.2 Soil water storage and movement

2.3 Soil water balance

2.4 Conclusion.

2.1 Flows of water over the soil surface

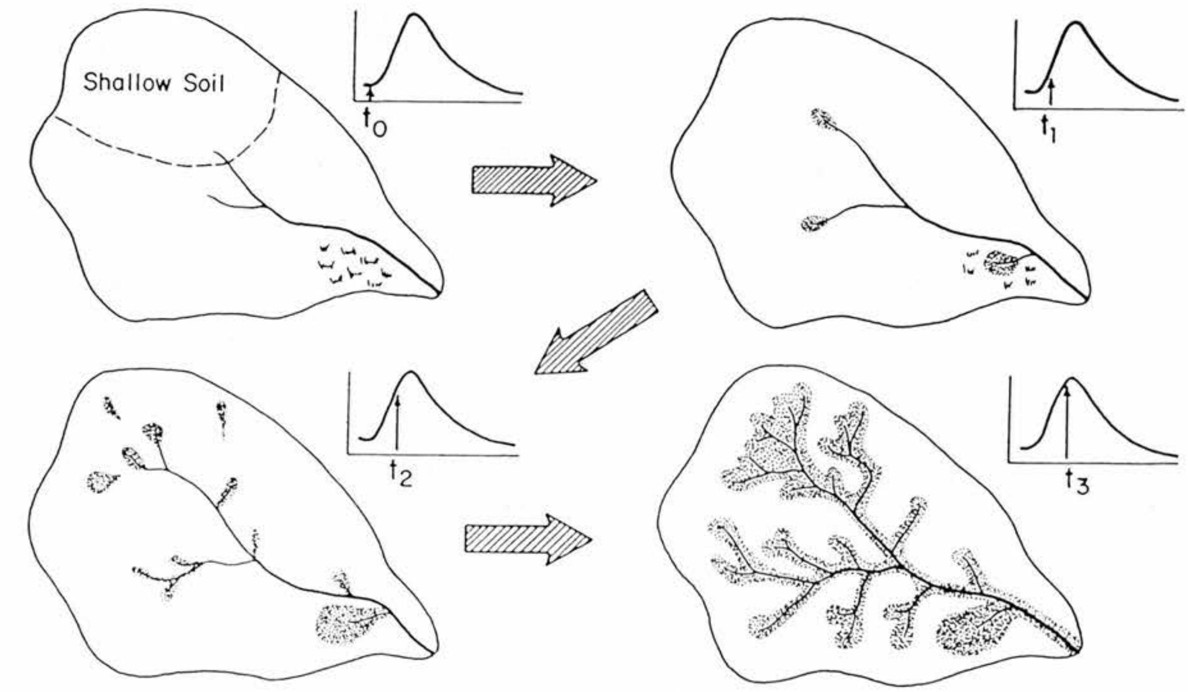
Pioneering studies about the measurement of water flows over the soil surface began with the contributions of Horton (1933). Horton's ideas to explain runoff were subsequently to dominate hydrology and its application to the prediction of streamflow discharge over catchment areas. Central to his analysis was the premise that infiltration divides rainfall in two parts, which thereafter pursue different courses through the hydrological cycle. One part passes to the stream over the surface of the soil, if the intensity of the rainfall event is in excess of the soil infiltration rate. On the other hand, when the intensity of the rain does not exceed the infiltration capacity, the water drains initially into the soil and thence through the groundwater flow to the streams or else it is returned to the atmosphere by evapotranspiration.

However, although widely used in hydrology and engineering, there were conflicts between Horton's ideas and the results obtained from observations by other authors. Some of these earliest observations were by Hursh (1936) and Hertzler (1939), who recognized subsurface flows as an important component of streamflow. Further, Hursh (1944) emphasized the hydrologic significance of the different soil horizons as related to water storage and soil water movement and he underlined the importance of understanding subsurface flow in order to provide better interpretations of streamflow hydrographs. Important contributions were also given by Hursh and Brater (1941) and Hoover and Hursh (1943), all demonstrating the need to account for subsurface flow when explaining streamflow, especially from forested upland catchments.

As summarized by Whipkey and Kirkby (1978), recognition of the importance of subsurface stormflow in the generation of streamflow, has developed from conflicts between field observations of small plots and the assumptions of traditional hydrological models for entire catchment basins. The first conflict arises because whole basin models relate peak stream hydrographs to widespread surface water flows within catchments, caused by rainfall intensities greater than the soil infiltration capacity. However, evidence from field observations contradicted this conclusion showing that flows over the surface of the soil need not occur at all, or may only be confined to small parts of a catchment, and also that soil infiltration capacities need not be exceeded for surface water flow to occur. The second conflict between whole basin studies and small plot observations arises because low streamflows, after rainfall, are normally related to the fall in groundwater flow rates. However, long recession curves with streamflows continuing for periods greater than one month may occur, in some cases, without any identifiable groundwater body. From these observations, it was concluded that flood peaks may be generated, in at least some circunstances, by subsurface stormflow. In other words, that part of the streamflow which derives from subsurface sources but arrives at the stream channel quickly, and becomes part of the storm hydrograph produced directly by a given rainstorm.

In view of this, it was soon realized that in order to explain and predict the behaviour of water, the movement of nutrients and pollutants and even the nature of soil erosion, there was a need for an understanding of source area processes. The Horton runoff concept does not provide this type of information and this gave rise to what has become known as source area hydrology.

The variable source area concept was proposed from the experimental work and field observations of Hewlett (1961) and Hewlett and Hibbert (1963) at the Coweeta Hydrological Laboratory. The concept was proposed to account for the fact that neither stormflow (the sum of surface and subsurface flows during storm periods and a major contributor to most floods), nor baseflow (ground water flow), is produced from everywhere within the catchment, either from surface or subsurface contributions. Instead,



Legend: - The small arrows at times t_0, t_1, t_2 and t_3 show the increase of the streamflow discharge as the variable source area expands into marshes, shallow soils and ephemeral channels.

Fig. 2.1 Source area and stream system expansion (after Hewlett, 1982) the flow of water in a stream at any moment in time is under the influence of a dynamic and highly variable source area, normally representing a small percentage of the basin area (Hewlett, 1982). The above concept is depicted in Fig. 2.1.

Fig. 2.1 is a time-lapse view of a permeable basin with a dendritic drainage network, showing the expansion of the source area and the channel system. The size of the area actively involved in producing stormflow will vary from less than 1% of the basin during light storms, up to more than 50% in extreme storm events. Observations in the southern Appalachians, in the areas where de-forestation had taken place, indicated a expansion of the source area to more than 80% of the basin (Betson, 1964). Later work carried out by the Tennesee Valley Authority (1966) in the same vegetated region, showed that the contributing area to stormflow might be expected to vary between 5% and 20% of the total basin, depending on the magnitude of the storm and the antecedent soil moisture.

As pointed out by Hewlett (op.cit), stormflow and its source area increases at the beginning and decreases at the end of a rainstorm as the result of two concurrent, and virtually inseparable processes: subsurface flow and channel expansion, depicted in Fig. 2.2.

Fig. 2.2 shows the disposition of the precipitation over a basin, and the solid black arrows in the soil mantle represent the effect of a large rainstorm as the distance upslope increases. Precipitation on the ridgetop makes only

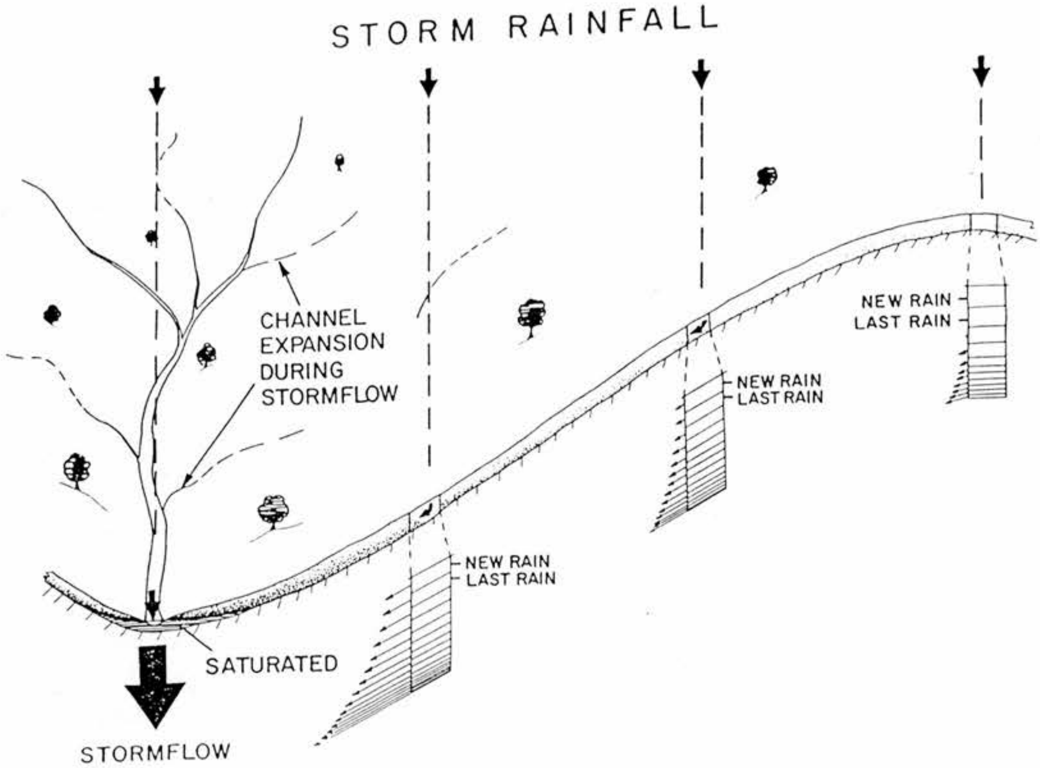


Fig. 2.2 Hypothetical section of a basin, showing the variable source area for stormflow and the source of delayed baseflow (after Hewlett and Hibbert, 1967)

a minor contribution to stormflow, although infiltration and downward movement of water within the soil profile begins to displace stored water downslope. Over the middle and lower slopes, rapid subsurface flow is moving through the soil mantle and displacement of stored water in deeper layers is more effective. This model goes some way to explain the diversion of the subsurface flow in the soil mantle close to the surface. However, field measurements suggest that this diversion of the subsurface flows may occur at increasing depths.

The conditions for subsurface stormflow generation are encountered in layered soils. Gradual changes in soil properties, such as a continuous decrease in hydraulic conductivity with depth, subjected to suitable antecedent moisture and rainfall conditions, may lead to saturation of a soil layer, and above and within this layer subsurface flow will occur downslope. As pointed out by Whipkey and Kirkby (op.cit), in coarse textured soils a normal profile sequence of soil horizons from litter to a partly organic A horizon to an illuviated B horizon, represents a sequence of reducing porosity and increasing clay content. This therefore tends to promote subsurface flows and experiments like those reported by Whipkey (1965) and Weyman (1973), measured appreciable quantities of subsurface stormflow in soils following this pattern. Fig. 2.3 shows an hypothetical section of a layered profile where subsurface stormflow occurs. This diagram, shows the generation of subsurface flow close to the surface in a two layered soil after a steady rainfall of long duration. The length of the arrows is proportional to the magnitude of the subsurface flow discharge. Thus, close to the top end of the plot, the small subsurface flow discharge can be balanced by downward movement into a shallow saturated layer within the impeding layer (K_2), where vertical movement is rapid due to a high diffusivity gradient. As subsurface flow discharge increases downslope, there occurs an increase in the saturation depth within the impeding layer, in order to support the increase in the subsurface flow discharge. Such increase in depth of the saturation, reduces the diffusivity gradient and hence the percolation rate into the impeding layer, until a point is reached, where not all the rainfall can enter the impeding layer. Below this point a saturated layer begins to back up in the upper, permeable layer. The above figure shows a situation in which most of the water moves down through the impeding layer (K_2) but most of the lateral flow occurs in the permeable layer (K_1).

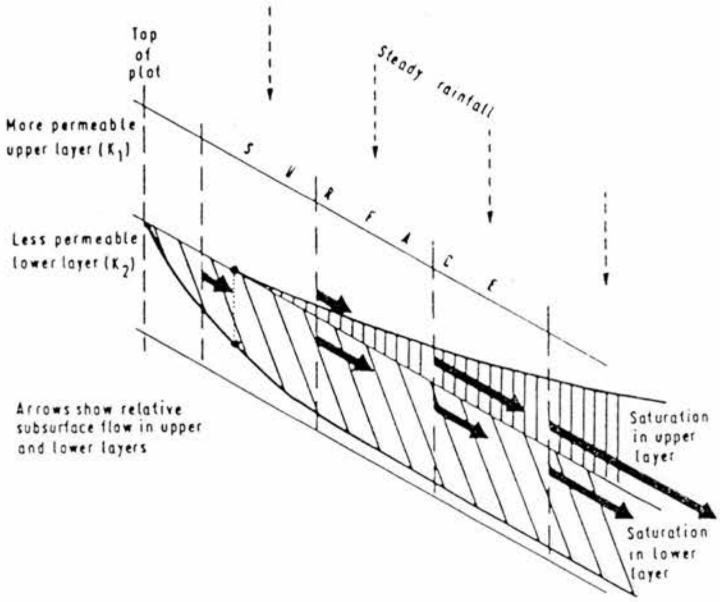


Fig. 2.3 Saturated soil layers and subsurface flow above and below the contact impeding layer (after Whipkey and Kirkby, 1980)

Channel expansion (Fig.2.1) results after a prolonged rainstorm, and as it soaks the slopes, the capacity of the soil mantle near the stream to transmit subsurface flow is exceeded, and water emerges at the surface. An increase of the channel up to ten or twenty times its perennial length, can occur as a result of the formation of intermittent and ephemeral channels by this emerging water.

The basic assumption of Hewlett's model, as oppposed to

Horton's runoff model, is that infiltration is seldom a limiting factor and consequently flows over the soil surface (overland flow) have to be treated as a special situation rather than a typical situation. In humid well vegetated areas, Hewlett's field observations indicated that most precipitation infiltrates into the ground and even during a 100-year storm event that delivered more than 500mm of rain in five days, in one of the Coweeta catchments, no surface flows were detected (Hewlett and Nutter, 1970).

Such observations questioned the range of validity of Horton's runoff model, especially for humid and well vegetated areas where infiltration rates are so high that few rainstorms have intensities that exceed them. As pointed out by Dunne (1978) when reviewing his own field observations, it appears that flows of water over the soil surface mostly occur on lawns, roads, tracks around water holes, and on many areas where soils have been compacted by the passage of animals, vehicles or people.

At present, Hewlett's model, embodying the variable source area and subsurface flow concepts, has become firmly established in hydrological theory, especially through the works of Dunne and Black (1970) and Anderson and Burt (1978), who accurately delineated the source areas of stormflow and showed the significance of hillslope hollows in the drainage process.

Between Hewlett's and Horton's model, which described the disposition of water over catchments, lie a variety of models in which the stormflow hydrograph peak is conceived as being composed of a varying mix of flow types (Chorley, 1978).

In relation to the present research project, which was set up on a freely drained soil (sandy-loam) with the aim of describing the flow process over a hillslope segment, the general premise about the disposition of water downslope was taken to follow Hewlett's model. It is however useful, at this point, to review a model which can describe the behaviour of the water flows within the shallow layers of the soil profile. This model is the percolation and leaching model proposed by Burns (1974) and used originally to predict the redistribution of salts in a sandy-loam soil profile.

Burns set up his experiment at Wellsbourne, England and the results in the early stages of the experiment indicated that when evaporation exceeded precipitation upward movement of water and anions of chloride and nitrate took place. Later, during periods of heavy rainfall, after the soil water was brought to field capacity, leachates moved in a downward direction through the soil profile. During the whole period of observation (May to October) although evaporation represented the major loss of water, significant quantities of water were lost as deep drainage. For an input of 198mm of rainfall, 145mm evaporated and 65mm was lost as deep drainage and no subsurface lateral flow was reported to have occurred.

However, even considering that Burns' model can explain the behaviour of the water flows in the shallow layers of the soil profile, it is not possible to overlook the fact that the ultimate disposition of the deep percolated water to the stream, may have followed a subsurface flowpath as described by Hewlett's model. This matter will be dealt with later in Chapter 5.

The course of hydrological research following the conceptual basis established by Hewlett, has provided detailed evidence of the processes of subsurface flow and of the variables which control the size and extent of the saturated zone on the hillslope (Weyman, 1973; Anderson and Burt op.cit). There has also been much interest in the generation of streamflow by subsurface water movement and in the denudational work accomplished by subsurface flows (Mosley, 1979 and 1982; Beven 1981; Beven and Germann, 1981; Burt et.al., 1984; Mosley and Rowe, 1984).

Attention has also been focussed on examination of the environmental factors responsible for variations in the patterns of flows across valley-side slopes (Arnett, 1974). Arnett discarded the influence of rainfall affecting the variability of subsurface flow, by assuming in his experiments that rainfall amounts and intensities remained constant over both valley-sides. In his analysis of temporal and spatial variation of subsurface flow he concluded that slope angle, length, surface roughness and soil texture had little effect on the observed flow patterns, whereas variation in permeability between topsoil and subsoil partially explained subsurface flows variations, between all sites in any given week, and at each site throughout the year. An interesting observation in Arnett's work is the different flow amounts between his two adjacent experimental areas. Both areas were freely draining brown earth soils; one covered with rough pasture grassland (Holcus lanatus, Festuca rubra and Agrostis canina) with a slope angle of 14.5° produced lower flow quantities than the other area covered with bracken (Pteridum aquilinium) with a slope angle of 17.6°. The work also gave a useful indication of the high variability of permeability between topsoil and subsoil, which permits an evaluation of the influence of this variable in the variation of runoff amounts. More recently, other authors have worked on the environmental control factors for modelling purposes, for example topography and precipitation and their relationships with overland flow generation. These include the works of Bryan et al. (1978), Morgan (1980), Anderson et al. (1984), and Hjelmfelt and Burwell (1984), which show that overland flow discharges are notoriously variable, at a small plot scale.

Considerations of error are an essential part of scientific research since they allow comparisons between results of different experiments. However, there is still a lack of assessment of measurement errors and evaluations of their influence in interpreting results in the literature dealing with measured flow processes. Such is the case in the recent publications by Carter (1983) and Baloutsos (1985). The omission of any error assessment has already been pointed out by Davidson (1978) who was dealing, in general, with experimental results in physical geography. It appears, as pointed out by Davidson, that this problem is due in part to the fact that the concern of the researchers is mainly to establish patterns in space and time which can then be interpreted. The omission of consideration of errors can also be due to the degree of instrumentation, labour and time involved in the study of such large scale processes - factors which may restrict the utilization of replicate plots.

It was with the above framework in mind that the present project was planned particularly to include replicate plots. The work, in following up the ideas proposed by Hewlett, attempts to extend the available information on flow processes over a hillslope segment. The results presented later will include an assessment of the error involved, and they can therefore be used as reference values for the variability of the flows over hillslopes of similar soil type, vegetation and under similar rainfall conditions.

2.2 Soil water storage and movement

Often the soil is considered as a water reservoir with a definite measurable storage capacity and, in this study, attention will be paid to considering changes in soil water content as a means of explaining the flow processes over a hillslope. Thus this section deals with a brief review of the basic ideas concerned with soil water storage and movement pertinent to this research.

Most of the water content of a well drained soil comes from rainfall or, in appropriate climatic environments, from melting snow which infiltrates as seepage water moving by gravity and surface tension through the pore spaces (Shaw, 1983). Subsequently, excess water within the soil pore space may be lost either as deep drainage or evapotranspiration.

As remarked by Ward (1975) based on Terzaghi (1942) ' If gravity were the only force to which water in the soil were subjected, the soil would drain completely dry after rainfall- the only water to be found being that below the water table'. However, the fact that in natural conditions soil always contains some moisture, even after prolonged dry periods, shows that soil moisture is held by strong forces in the soil matrix. This implies that soil water retention and movement constitute two important phases of soil moisture relationships.

The early concepts in the literature, relative to soil water relationships, were primarily based on the capillary-tube hypothesis proposed by Briggs (1897) who conceived the idea that capillary water existed as a continuous and tightly stretched film around the soil particles. The forces arising from the curvature of these capillary water surfaces were taken as the main cause for the retention of soil moisture. The retention of soil moisture would then be dependent upon the number and size of these capillary spaces. According to this notion, water movement occurs from the thicker to the thinner films, and the rate of movement is related to the difference in curvature of the films, the surface tension and the viscosity of the liquid (Baver, 1965).

Soil water according to Briggs may be classified into three phases:

(1) Hygroscopic water, i.e. water absorbed from an atmosphere of water vapour as a consequence of attractive forces on the surface of the soil particles

(2) Capillary water, held by surface tension forces as a continuous film around the soil particles and in the capillary spaces

(3) Gravitational water, which is the water held by the soil at such low tensions that it can drain from the profile under the influence of gravity.

Ten years later Buckingham (1907) introduced the idea that the flow of water through the soil could be compared to the flow of heat through a metal bar or to the flow of electricity through a wire. The driving force, or the cause of the capillary current, was the difference in attraction for water between two portions of the soil that are not equally moist. Buckingham suggested the term 'capillary potential' to express the value which measures the attraction of the soil at any given point for water. However, the ideas of Buckingham did not receive serious consideration until they were expanded by Gardner (1920), who pointed out that the 'capillary potential' gave a new interpretation to the various soil-moisture constants employed by Briggs and others.

The energy relationships in soil moisture retention and the capillary potential notion proposed by Buckingham were of vital importance for the understanding of the soil moisture relationships. From this concept it was established that soil moisture could not satisfactorily be differentiated by type, such as in the classification proposed by Briggs, but can only be differentiated by its potential-energy condition. This potential energy status can be related to the quantity of water stored in the soil and the potential gradient can be related to the rate and direction of soil water movement.

The notion of 'capillary forces' as proposed by Buckingham, acting upon the water in the soil pore space was later criticized by Childs and George (1948). They pointed out that there were at least four components to the total force involved:

(1) The gravitational potential, which is the work done in lifting a unit volume of water to a given elevation above a fixed level.

(2) The pressure potential P, which is the work done in taking a unit volume of water from zero pressure to a point where the pressure is P. Under a water table, P is positive, whereas in unsaturated soil P is negative, and is normally referred to as the matric potential.

(3) The osmotic potential, which is related to the movement of water from areas of low solute concentration to areas of high solute concentration. This potential is usually negleted in soil but it is fundamental in plant-water relationships.

(4) The adehesion potential which is due to the attraction of oriented dipolewater molecules on the surfaces of the soil particles.

The notion of the total potential therefore arises from the combined effects of these four forces. It is recognized that the different components of total potential do not act in the same way, and that their separate gradients may not be equally effective in causing flow of water. Nevertheless, as pointed out by Hillel (1982), the principal advantage of the total potential concept is that it gives a unified measure by which the state of water can be assessed at any time and everywhere within the soil-plant-atmosphere continuum.

The negative pressure potential has often been termed 'capillary potential'. However, as pointed out by Ward (op.cit) and Hillel (op.cit), this term is not adequate since adsorptive and capillary forces operate in the soil. Furthermore, the determination of the separate effects of capillary and adsorptive forces on the negative pressure is difficult, since the capillary edges are in a state of internal equilibrium with the adsorption films and neither can be changed without affecting the other. In addition, the presence of solutes lowering the water potential energy must be taken into account, especially when dealing with plant water relationships. Therefore, instead of 'capillary potential' a more adequate term to express the negative pressure potential of soil water is used, namely the matric potential, which expresses the effect resulting from the affinity of soil water to the whole matrix of the soil, i.e. its pores and particle surfaces together.

Turning to soil water storage, as the soil dries out, removal of water starts in the large pores where water is held least strongly by the attractive forces of capillarity and absorption. As drying proceeds, the remaining water will be held with increasing attraction in sucessively smaller pores and thin films. As the attraction of the soil for water lowers its potential energy, it is possible to distinguish a clear relationship between the quantity of water retained in the soil and the soil water potential. In relation to its movement through the soil profile, soil water tends toward equilibrium energy conditions, and therfore moves from points where the total potential is high to points where the total water potential is low. If the total water potential at point 'A' in the soil for example, is -50cm of water and the total water potential at point 'B' is -20cm of water, then water will move from point 'B' to 'A'.

Most of the applications of the energy status of soil water and the rate and direction of its movement in the soil profile, is found in agriculture particularly in irrigation studies. As exemplified by Hanks and Ashcroft (1980), the root zone for most agricultural plants is limited to the unsaturated part of the soil profile. Thus, in non saline soils, the 'water comfort' for plants is largely determined by the matric potential of the soil water. As the matric potential at which water should be applied for maximum crop yields is known, it is possible to schedule irrigation by monitoring the soil water potential.

To express the macroscopic flow of water within the soil, a mathematical relationship was first postulated by Darcy (1856). It is commonly expressed as follows:

$$V = - K \, \mathrm{grad} \, \phi \qquad (2.1)$$

This states that the flow of water in a porous material (soil) is proportional to the hydraulic potential gradient. In the above expression V is the volume rate of flow per unit area, K is the hydraulic conductivity of the soil ϕ is the hydraulic potential (measured at two positions saparated by a distance L along a straight line parallel to the direction of the flow).

As pointed out by Youngs (1965), Darcy's original experiments were conducted by filtrating water through beds of saturated sand and equation 2.1 was thus formulated to describe flows in saturated porous beds. However, through experiments conducted by Childs and George (1950), who observed flows in unsaturated material with various hydraulic potential gradients, it is now generally recognized that Darcy's equation can be used to describe flows in both saturated and unsaturated porous materials.

In order to obtain a general equation to describe the water movement through porous material (soil) when desaturation is occurring, Darcy's law and the law of the continuity may be combined. The continuity equation, in its simplest form, states that any change in water content within an infinitesimal volume of soil must result from a net input or output of water to that volume.

$$\frac{\delta c}{\delta t} - q = \text{div } V = \text{div } (K \text{ grad } \phi) \qquad (2.2)$$

where c is the moisture content at a given point at time t and q is the rate per unit volume of water abstracted at that point.

Turning to the problem of the movement of the water in field soils, it is useful to mention in this review a laboratory experiment demonstrated in Brady (1974) dealing with the dowward movement of water in stratified soil (Fig. 2.4). This figure is important in the context of the present research because it gives an idea of the importance of the potential gradient between soil layers, influencing the movement of water within the profile.

Fig. 2.4A shows that at the end of time t1 downward movement is no greater than lateral water movement, indicating that in this case gravitational force is insignificant compared to the potential gradient between wet and dry soil. On 2.4B the downward movement stops when a coarse textured layer is encountered, after time t2 no

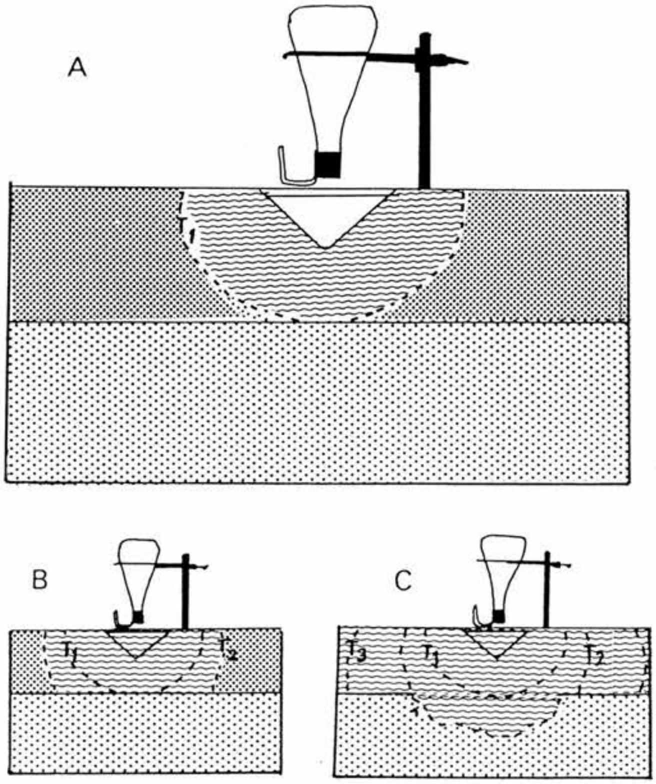


Fig.2.4 Downward water movement in stratified soils (after W.H. Gardner, quoted in Brady, 1974, p.187)

movement into this layer occurs. Only after time t3 , (Fig. 2.4C) when the moisture content of the overlaying layer becomes sufficient to produce high enough potentials is there a downward movement into the coarse layer.

The first part of this assumption is supported by authors such as Hewlett and Troendle (1975) who stressed the anisotropic character of the soil profile which restricts vertical flows of water. The water then responds to changing hydraulic potential gradients flowing more or less parallel to the slope surface, depending on local moisture contents, soil hydraulic conductivities and the steepness of the gradient. A helpful explanatory aid to this behaviour of water is given by the 'straw roof' analogy proposed by Zaslavsky and Sinai (1981), shown below in Fig. 2.5.

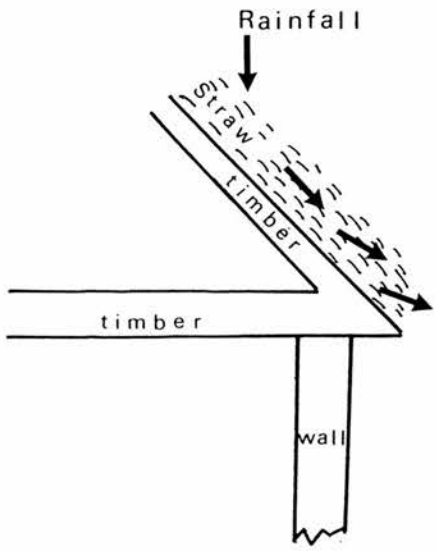


Fig 2.5 Straw roof analogy for the movement of water within the soil (after Ward, 1984)

This analogy shows that during the rainfall the building remains dry, no water runs over the thatch as 'surface flow' and there is no evidence of 'groundwater' or zones of 'temporary saturation' i.e. all the water is drained along the narrow layer of the thatch. The straw roof works by disposing the water laterally, because the alignment of the straw conveys a preferential permeability along the stems and because of the slope of the roof. In the case of the soil mantle, it is known that whether or not an impeding layer exists in the subsoil, there is preferential hydraulic conductivity through the open textured upper layers parallel to the surface. This operates in such a way that where soil covers a uniform slope it would behave like a straw roof, implying that the rainfall infiltrates and is disposed as lateral flow, without passing either as vertical (percolation) or surface flowpaths (Ward, 1984).

Gardner's experiment and Zaslavsky and Sinai's 'straw roof' analogy are important since they can help in the explanation of the observed pattern of water flows, especially in the case of lateral flow generation. Through the use of the concepts of energy status of the soil water, reviewed in this section, it will be possible to make statements about the temporal pattern of the outflow from the artificial plots. This matter will also be dealt with in Chapter Five.

2.3 Soil water balance

As the soil water balance provides information on periods of water surplus and deficit, it permits an assessment of the water stored in the soil or of the loss as runoff or deep drainage at any given time. It becomes a basic tool in any avaluation of the water problems of a region or of a specified area.

In broad terms, water balances can apply to oceans, continents, lakes and reservoirs. As pointed out by Sellers (1965), the water balance equation of the earth surface is a mathematical formulation of the part of the hydrologic cycle that deals directly with the air-land or air-water interface.

In such large scale studies, authors such as Budyko (1956), Budyko et al. (1962) and McDonald (1961) give the annual water balance for various oceans and continents. From the data provided, it is possible to conclude that as whole, the oceans lose more water by evaporation than they gain by precipitation, the deficit being made up by runoff from the continents over which precipitation exceeds evaporation.

The notion of large scale water balances, also allows recognition of the fact that the world's wettest major geographical region is South America. South America receives 1350mm of precipitation annually (more than twice the quantity received annually in Europe), losing two thirds of this as evaporation and the remainder as runoff discharged in the ocean.

As remarked by Sellers (op.cit), the water balance of the earth's surface deals with only part of the hydrologic cycle. A complete picture can only be given by considering the water balance of the atmosphere. Since the present research deals only with the soil water balance restricted to part of the hydrological cycle, specifically with the changes of stored water in the soil, it is not considered relevant to include a review of the atmospheric contribution here.

Several models of water balance have been used for agricultural purposes, for instance the utilization of water and energy by crops. Among the most important there are the models of Thornthwaite (1948), Prescott and Thomas (1949) and Turc (1954; 1955).

In the early 1930's Thornthwaite became aware of the importance of the soil moisture factor in climate studies and concluded that he could not gauge the dryness or wetness of a climate by considering precipitation alone, but he would need information on evaporation as well. Later, when faced with the problem of determining water needs for irrigation, he realized that it was not possible to determine the amount by which precipitation fails to supply the water needs of crops, unless one knows what these needs are. This very important climatic element was defined as the amount of water which will be lost from a moist soil surface completely covered with vegetation and it was called potential evapotranspiration. The concept of evapotranspiration dates from 1924 and it was originally employed to provide information on the water needs for vegetation and in solutions of problems of stream flow and ground water storage. The empirical formula which served for the calculation of the potential evapotranspiration became the foundation of Thornthwaite's climatic classification of 1948, which proved a more rational interpretation of the moisture factor. The development of these ideas meant that it was possible to work out the water balance of an area gaining new insight into its site qualities by determining potential and actual evapotranspiration and water surplus deficit.

A method for calculating the water balance which allows the determination of the change in soil moisture, soil moisture deficit and surplus, and runoff is outlined in Thornthwaite and Matter (1955). This method has been used for a great variety of purposes and has been modified many times. Examples of the use of the water balance are in the definition of drought and scheduling of supplemental irrigation, and in the determination of stream runoff and fresh water accession to coastal estuaries (which help in the determination of the salinity and density of water). Through the water balance, it is also possible to determine the frequencies of moisture stress days for each part of the growing season in a particular region. However, although the models of Thorntwaite and other authors have been largely used for agroclimatic purposes, there are criticisms concerning their utilization since, in most cases, the plant-climate relationships for which they have been used have been so non-critical as to make predictions extremely qualitative. More accurate models based on specific physiological and environmental parameters (Monteith, 1965; Cowan, 1965) have already proved to be adequate for the understanding of plant-environment relationships, but again these models have limitations since they cannot be applied to situations where limited environmental data are available unless several simplifying assumptions are used.

At present, soil water balance information is regarded, in some ways, to be most useful in solving the existing conflict concerned with the use of simplified models which yield qualitative predictions. It is also useful in solving the difficulties in the application of accurate models in regions where crop and environmental data are not available. It is recognized however, that the soil water balance can only give realistic estimates of the length of the growing season if water supply is the primary factor determining growing season characteristics (Slatyer, 1968).

Furthermore, the soil water balance is widely recognized to provide a key to the variations of the soil moisture content and hence soil water potential, a factor of great importance both in plant growth and in the functioning of ecosystems. The importance of the soil water balance rests on the fact that of all the reservoirs or pools in the ecosystem where water is stored, the soil reservoir is the most crucial. The water stored in the soil profile reservoir, although often smaller in volume than the ground water body, is more accessible for biological utilization and its fluctuations both reflect and control the moisture status of the plants (Miller, 1977). The soil water balance equation is generally writen in the form:

$$P - R - D - E + \Delta W = 0 \qquad (2.3)$$

where P, R and D are the precipitation, runoff and deep drainage respectively. Deep drainage is generally defined as the quantity of water passing beyond the root zone, or, for experimental purpose, the amount passing below the lowest point of the measurement. E is evapotrasnpiration and ΔW is the change in soil water storage.

An interesting example of a soil water balance study is the work of McGowans and Williams (1980) for an agricultural catchment in England. The authors described a graphical method for distinguishing between drainage and evaporation from the soil, based upon the identification of the maximum depths at which measureable quantities of water are extracted by the plant roots. From graphs of soil water content versus time at different depths, McGowan and Williams observed that during dry periods an initially slow, almost non-existent rate of water loss, was followed by a more rapid removal of water by roots. Analysis of such graphs illustrated gave the progress of the drying front down a soil profile allowing the definition of the 'effective rooting depth' of a crop (i.e.the maximum depth from which measurable quantities of water are extracted by crop roots).

Support for this observation came from an analysis of associated tensiometer data first presented by McGowan (1974). Profiles of the hydraulic potential were used to identify the depths at which the gradient of the hydraulic potential is zero and thus the net flow of soil water is zero, i.e. the 'zero flux plane depth'. Thus above the zero flux plane the potential gradient and hence the water flux is in an upward direction supplying the evaporative demand. Below the zero flux plane the flows are in downward direction reflecting drainage through the soil profile. Fig. 2.6 depicts the concept of zero flux plane:

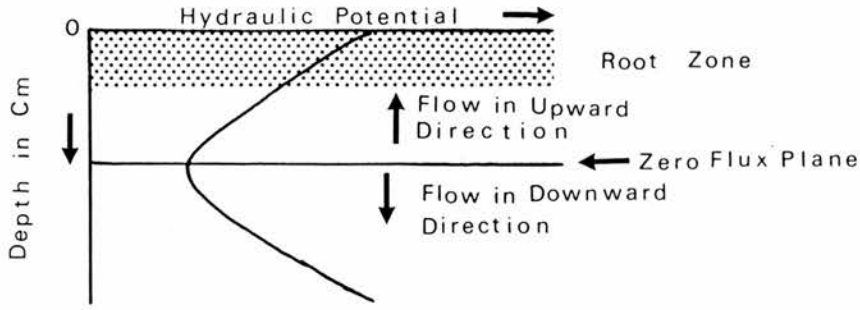


Fig. 2.6 Zero flux plane defined within the soil profile, from tensiometer data (after Bell, 1976)

A good agreement was observed between the drying depths derived from the water content/time graphs and the zero flux plane depths observed in the hydraulic potential profiles (McGowan and Williams, op.cit).

2.4 Conclusion

From this selected literature review, it is possible to see that previously published work dealing with water movement over sloping surfaces tended, at first, to be dominated by the notion that infiltration was a key factor. Infiltration appeared to divide the rain water in two parts: (1) flows over the soil surface (overland flow) and infiltrating water which reaches the streams as ground-water flow. Gradually, conflicts between these ideas and data from field experiments, showed that infiltration was not a limiting factor, and that much of that streamflow is due to the contribution of subsurface flows rather than overland flow. These notions included the variable source area concept, extending its application to humid-areas, whereas the old concept (Horton's runoff model) was limited to semi-arid areas or places disturbed by man's activities.

Ideas about the role of subsurface flow to streamflow were confirmed by several field observations and research moved towards the determination of the spatial variability of source areas of subsurface flows. Interest was also focused on the determination of the enviromental factors responsible for variations in the amounts of subsurface flows.

However, few of the research publications on flow processes over sloping surfaces give any consideration of the error involved in the results. This is a constraint which does not permit statistical comparisons nor the establishment of convincing trends or patterns.

Concerning the ideas of soil water storage, the notion of soil water potential was shown to be of vital importance. This concept showed that arbitrary classifications of types of soil water are meaningless, since these classifications did not permit the determination of soil water content, nor its rate nor direction of movement.

Finally, the concept of water balance has been shown to be useful at various scales. On a global scale, it is possible to understand the transport of moisture from atmosphere to litosphere, hydrosphere and biosphere and also it is possible to classify climates, especially for agricultural purposes. At smaller scales, catchments for example, the water balance concept permits the evaluation of errors in the components of the hydrological cycle and provides a check on the validity of hydrometeorological data, but most important, it enables a detailed identification of the seasonal patterns of water supply and irrigation demand in the planning for the development of the water resources.

Chapter Three

Environment of the study area

The catchment area which forms the framework for this study, is considered first of all in its regional context, in order to identify relatively permanent characteristics such as geology, relief and climate. The characteristics of the catchment itself are then considered with particular emphasis being placed on the vegetation and upon soil properties.

The original study was intended to be carried out at several sites on both valley slopes of Boghall Glen, a small east-west trending valley in the northern Pentland Hills (Fig. 3.1). Although a soil and vegetation reconnaissance survey was carried out over the two valley sides, logistic problems limited the work to a study of only the northern side of the valley and at only one site. These problems were related to initial difficulties in obtaining permission to work on the southern slopes, belonging to the Ministry of Defence, and also to the time and work load necessary to instal the sites and to carry

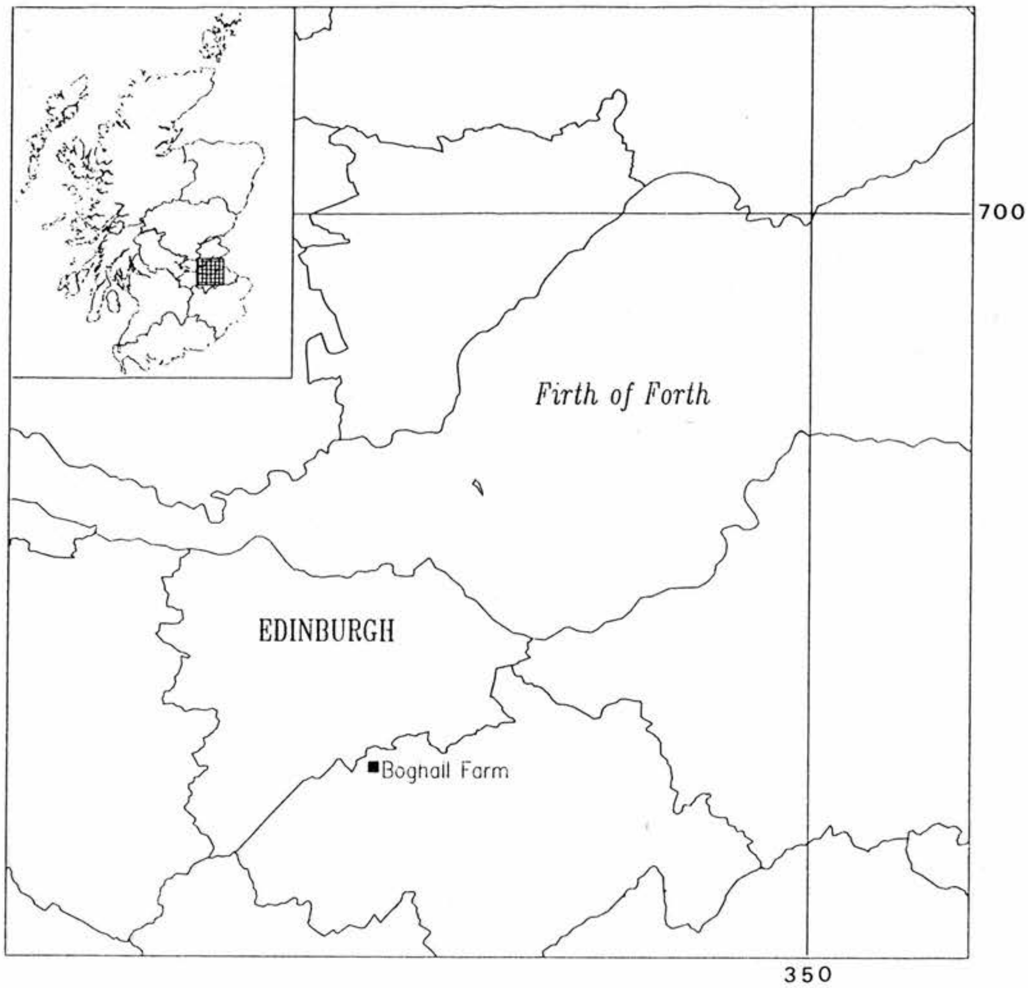


Fig. 3.1 Location of Boghall Farm

out the regular readings. There is only one track suitable for wheeled vehicles (Fig. 3.2) and since access was of particular importance in setting up the installations at each site, this constrained the initial site selection to an area within easy reach of pathway.

3.1 Geology and landforms

The study catchment is situated in the northern section of the Pentland Hills, which have a complex geological history and are characterized by a variety of rocks and physical features. The solid geology of the hill area mostly comprises acid igneous and metamorphic rocks, including Permo-Triassic andesites, granites, breccias and sandstones; Carboniferous sandstones, shales, grits and limestones; Upper and Lower Old Red Sandstones, conglomerates and sandstones; Ordovician-Silurian greywackes, shales and metamorphic rocks.

Lying over this varied assortment of parent materials, there exist different thickness of glacial lodgement and ablation till, and outwash gravels re-sorted by processes such as solifluction and mass movements (Sissons, 1976).

The geology of the catchment basin itself, is represented by conglomerates and pebbly grits from the basal beds of the Lower Old Red Sandstone. The rocks were originally deposited in a fluvial and lacustrine environment. A period of volcanic activity followed, now represented by lavas with thin interactions of tuff and sediments which forms the belt of high ground including the north end of the Pentland Hills, the Braid Hills and Blackford Hill. These volcanic rocks, probably deposited in subaerial conditions, attain a thickness of over 1800m in the Caerketton-Allemuir area.

The catchment is known locally as Boghall Glen, having its divide limited to the north and west by the Caerketton and Allemuir Hills and to the south by Woodhouselee Hill. Fig. 3.2 shows the location of the study site, to the Southern midslope of Caerketton Hill.

The area includes a diversity of relief with hills of 300m to 600m in altitude which rise from extensive areas of lowland surrounding the Pentland Hills. This physiographic region came into existence prior to Pleistocene glaciation, but the contemporary landscape exhibiits features characteristic of its glacial history. The region was engulfed by the principal Pleistocene icesheets moving off the Highlands to the north and west and Southern Uplands to the south which left behind thick deposits of lodgement till (Brown and Shipley, 1982). The present day soils and drainage are therefore determined partially by the glacial topography and parent materials and partially by the post glacial re-sorting of these deposits. The specific study site within the catchment is today covered by residual glacial deposits, estimated to be on average more than 3m thick.

3.2 Climate

The climatic elements considered in this section are those which most contribute to soil water movement and storage, notably insolation and rainfall. The importance of these two elements rests on the fact that insolation contributes the energy available for weathering and biotic

Boghall Glen

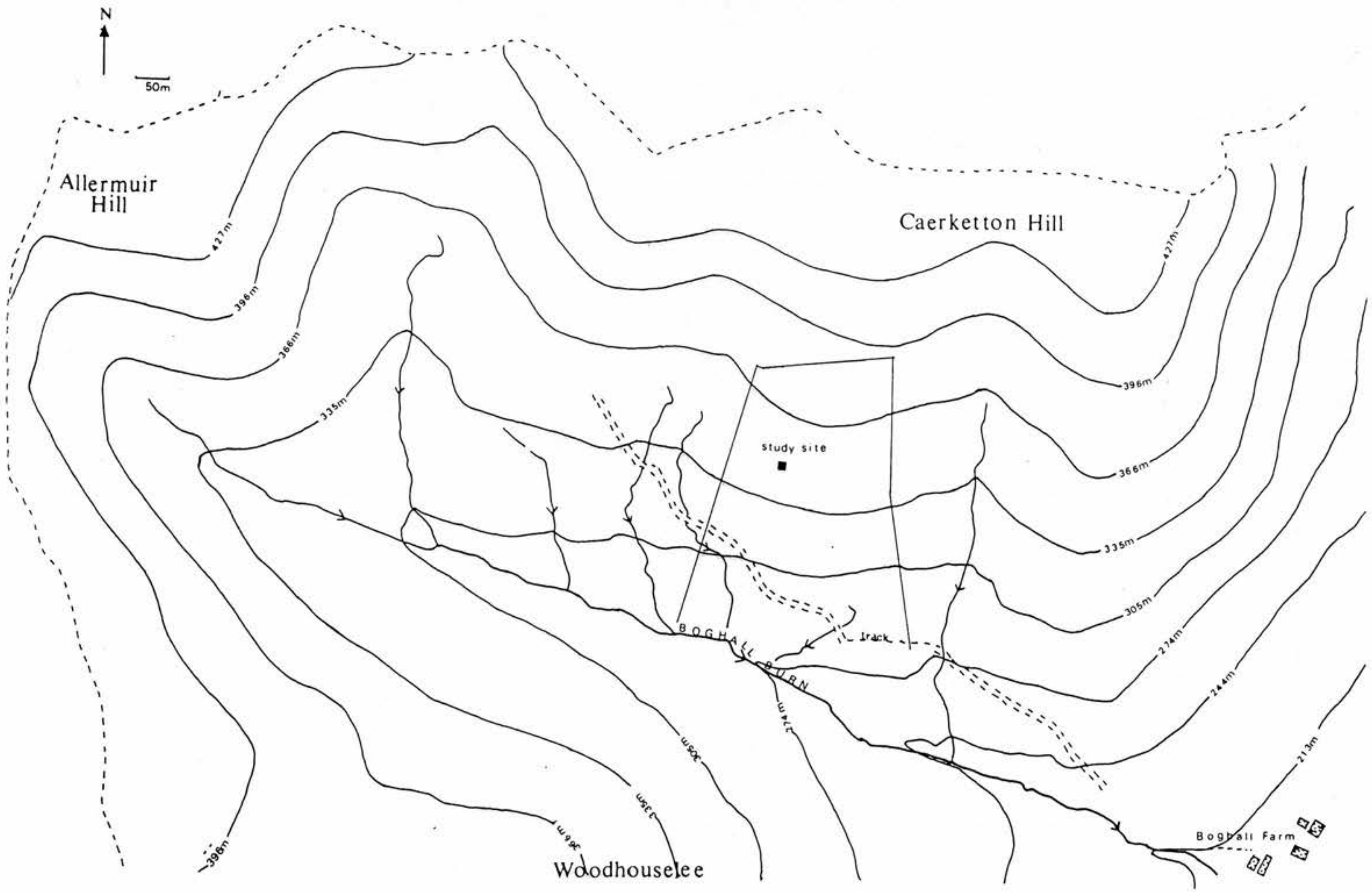


Fig. 3.2 Location of the study site (south facing slope)

activity in the soil and particularly to evaporation of soil water, whilst precipitation affects percolation, subsurface flows and, locally, processes such gleying.

The climate of south-east Scotland is generally equable and temperate, with moderate to high rainfall more or less evenly distributed throughout the year. There are few large fluctuations of temperatures. The wind regime is largely governed by the passage of north atlantic depressions associated with the Gulf Stream. Heavy showers and frontal rains are associated with these depressions where the air flows from the west are very much reduced along the east coast. This is mainly a result of the sheltering effect of the Southern Uplands. An opposing synoptic pattern with the high pressure centered in northern latitudes, can recur during the first half of the year. These winds are of a northerly and north-easterly type and occur as a cold unstable air sweeping over the country from the north or north east. The lowland area of south east Scotland can be protected by the highlands when the wind is northerly. A change in direction to the north or north-east is sufficient to bring showers or snow flurries over all of the south eastern Scotland. The predominance of westerly winds is shown by the anemometer data provided on Lowther Hill, which shows a frequency of nearly 60% of this wind direction especially occuring during the summer and autumn (Brown and Shipley, op.cit).

It is the interaction of the air flows, penetrating the

the south east region to varying degrees with the convoluted pattern of the main landforms, which governs the climate regime within the area. High levels of precipitation, over 2500mm per annum over high ground, reflect the rise of moist westerly winds over the hills. As the air masses move eastwards, moisture losses increase and the rainfall declines, 1000mm being the maximum annual figure on the easterly Moorfoot and Lammermuir Hills.

The catchment area of the present study, lying within in the general influence of the Midland Valley and part of the Pentland Hills physiographic region, has a low average of rainfall of 600 to 800mm per annum. The catchment is protected from the westerly moist winds by high ground (Plant, 1968). The distribution of rainfall in eastern areas normally indicates that winters are not very wet, spring and early summer are dry, whilst peak rainfall occurs in late summer (Ragg and Futty, 1967). The rainfall in the south east of Scotland has a coefficient of variation of 16% (Gregory, 1955). This yearly variation occurs as a response to the changeable atmosphere circulation and in particular to the location, intensity and duration of the main centres of depression and anticyclone activity over the British Isles as a whole. As an example, the first part of this study was carried out in 1984, when much of the year, and particularly the summer period, was dominated by anticyclonic circulation which prevented many depressions from following their normal routes near the British Isles. The second part was conducted in 1985, when much of the year and particularly the summer, was dominated by westerly cyclonic systems.

The anticyclonic circulation system in 1984 resulted in great water deficits experienced in the southern areas of the British Isles and to a lesser extent in Scotland. On the other hand, in 1985, the predominance of the westerly cyclonic system meant that areas to the east of the main uplands had considerably higher rainfall than average (as shown later in Table 5.1).

The temperature of the air is closely related to altitude and the Meteorological Office adopts a standard lapse rate of daily mean temperature with increasing height of 6°C per 1000m. Mean annual temperatures for the lowlands of the south east Scotland are in the range of 8°-9°C. For the study catchment, with an altitude of 250m, the estimated temperatures are in the range 7.1°- 7.3°C. The average value for potential evapotranspiration over south east Scotland is 450mm per annum and the annual actual evapotranspiration (AE) is around 400mm (Francis, 1981).

3.3 Water balance for south east Scotland

Similar to much of the British Isles, south east Scotland loses approximately 50% of its precipitation as evapotranspiration. The remaining precipitation either passes into the temporary storage of the soil and hence to groundwater, or runs off as surface runoff and eventually streamflow. As indicated by Ward (1976), the water balance in any catchment can be expressed by the following relationship:

$$P - E = \Delta S + \Delta G + Q \qquad (3.1)$$

where P is precipitation, E is evapotranspiration, ΔS and ΔG are changes in soil water content and groundwater storages and Q is streamflow discharge.

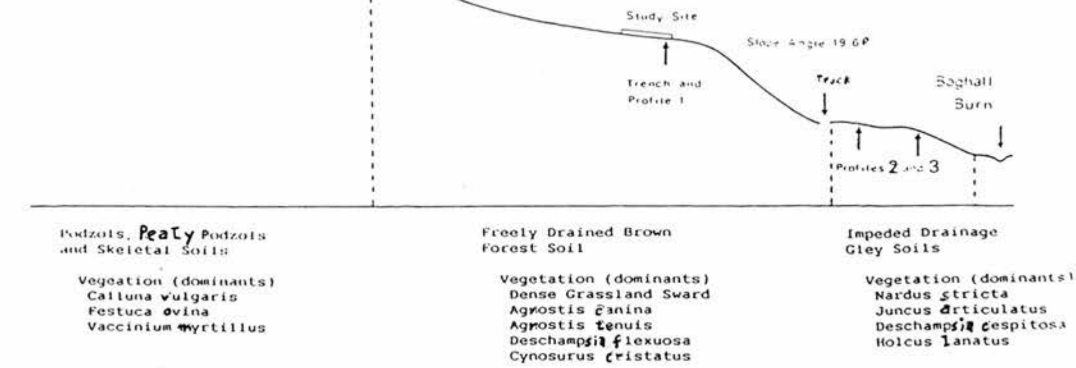
On those occasions when rainfall exceeds potential evapotranspiration, soil water content can reach its maximum, enabling a surplus of water to be generated for streamflow and for the recharge of groundwater supply. When potential evapotranspiration exceeds rainfall, there will be some withdrawal from soil water storage and, if these conditions continue, soil water storage will be depleted and actual evapotranspiration will fall below potential evapotranspiration, indicating a soil moisture deficit. For the hillslope segment which forms the object of the present study, it is assumed that actual evapotranspiration will equal the potential evapotranspiration until the soil remains at field capacity. For upland catchments in south-east Scotland, the soil water drops below field capacity in early March and returns to field capacity in mid-October (Francis, op.cit).

The wetness and dryness of the climate of south east Scotland can be defined by the magnitudes of the soil water surplus and deficit. In general terms, soil moisture defiicit can occur at any time of the year as evapotranspiration dries out the soil during rainless periods. It is recognized that these deficits are small during the winter, but considerable deficits may build up during the summer.

3.4 Vegetation

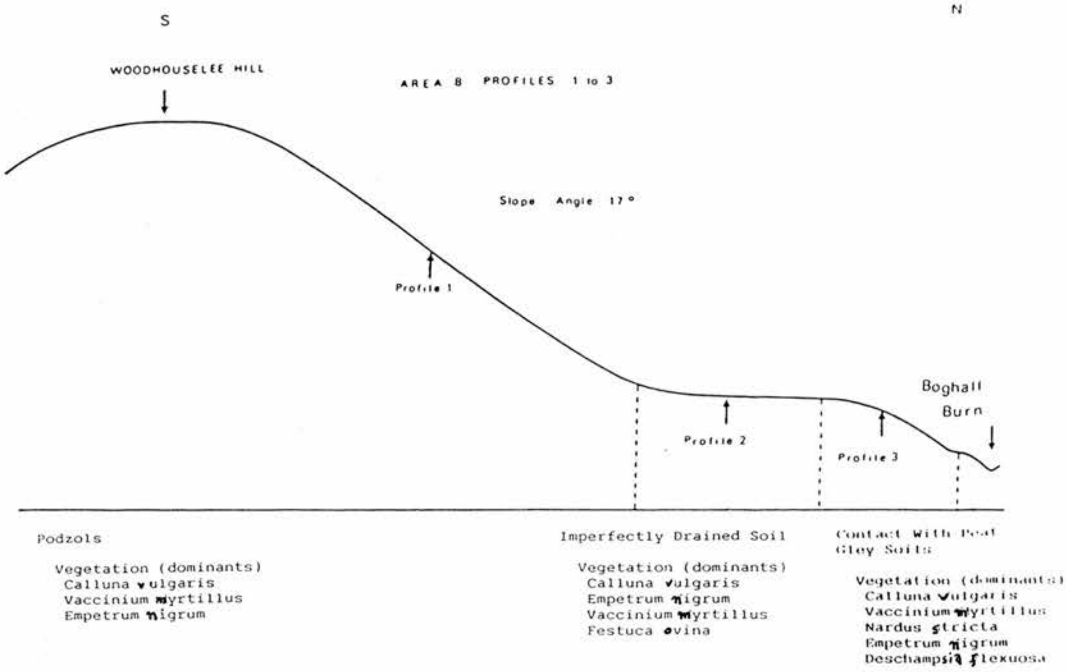
An early account of the vegetation at Boghall Glen has been given by Fenton (1951). In his report, based on aerial photographs, he distinguished sites of former cultivation, perhaps two hundred years old, which are today occupied by improved grassland. At present, most of the area of Boghall Glen is subject to agricultural activity which is predominantly pasture on the relatively steep slopes with some cultivation over the lower gentle slopes.

A vegetation survey was carried out on both valley sides and the main vegetation types are presented in Figs. 3.3 and 3.4. The pattern of vegetation may be summarised as



Distance from Caerketton summit to
Boghall Burn is: 500 m

Fig. 3.3 Schematic diagram of the south facing slope (Caerketton Hill)



Distance from Woodhouselee Hill summit
to Boghall Burn is: 600m

NB. Profile 3 represented here as if it were in a catenary transect, lies approx. 20m laterally from 2.

Fig. 3.4 Schematic diagram of the north facing slope (Woodhouselee Hill)

being dominated by heather moorland lying above wet rush and sedge grassland on the less disturbed north facing slope, with artic-alpine summit vegetation lying above a vaccinium-callunetum moorland above the improved dry and wet grassland on the slopes of Caerketton.

As it was pointed out earlier the project was carried out over a segment of the south facing slope, covered by improved grassland, in freely drained brown earth soils (Fig. 3.3). At this site, the results (as shown later) indicated a predominance of deep drainage over lateral runoff. However, the vegetation at the foot of the slope is typical of seasonally wet or, waterlogged soils and may indicate that subsurface water from the slope above can emerge at this point as saturated overland flow. This has been already observed by Whipkey and Kirkby (op.cit). Also this lower wet area indicates a source area of streamflow, which may expand during the wet period as observed by Hewlett (op.cit). Over the two field seasons, the grassland vegetation at the study site was regularly kept cut, thus reducing the effect of plant interception on rainfall.

3.5 Soils

The soils of the Pentland Hills are relatively young, dating from the last deglacial period (from c. 13000 BP) and following re-sorting by periglacial and slope processes. The better developed soils are formed in glacial deposits and, in addition, skeletal soils occur in recently weathered parent materal. Several properties of the parent materials, little altered by processes of soil formation, have been inherited by the present day soil profiles, whilst others have undergone substantial changes during soil evolution. Stoniness is a example of a property closely related to geological provenance and which has a major agricultural importance. Texture represents another inherited characteristic and has a major effect on the subsequent soil forming processes, such as leaching and gleying, through its predominant influence on soil moisture relationships. Soils found in coarse-textured parent materials are, in most cases, freely drained and strongly leached. This augments the natural tendency to acidity, leading to increased weathering and reduced biotic activity. At the other end of the textural spectrum, permeability to water is low in soils with high amounts of clay, leading to prolonged or periodic waterlogging, according to climate and topographic position. This situation is more characteristic of the valley bottom which appears to have developed in deep colluvial, probably soliflucted deposits. The fine fraction content is, however extremely variable. The wet conditions have favoured anaerobic and reductive processes with resulting surface water gley (stagnogley) properties dominating the soil profile. Groundwater gleys are common near stream base level and in depressions.

A wide variety of soils characterize the south-east of Scotland. Stony, medium-textured drifts cover smooth steep convex-concave slopes to depths ranging from 1 to 10m. The soils over the upper and midslope sites are characterized by rapid runoff and free internal drainage. Humus iron podzols are found over the upper slopes and with increasing altitude, whereas peaty podzols are found occupying summits below 600m. Humic and non calcareous gleys are generally found in valley bottoms at altitudes less than 250-300m. These differences are well reflected in the catenary sequences (toposequences) characteristic of the area. Well drained and severely weathered soils in the upper convex slopes tend to be podzolic, passing downslope to less leached brown forest soils over midslopes and changing to wetter gleyed profiles at the concave accumulation zones towards the footslopes (Soil Survey of Scotland Sheet NT 26 - 1:25000). The major associations and soil groups at Boghall Farm are: Bemersyde, Sourhope and Biel, with freely drained podzols, freely drained brown earths and gleys and peaty gleys respectively (The Soils of the Bush Estates, Midlothian, 1:10000).

A reconnaissance survey was carried out on both valley sides of the study catchment. This revealed a pattern of soil distribution similar to the general soil characteristics described above (Fig. 3.3 and 3.4).

The result of the preliminary soil analysis at the two sites is presented in Tables 3.1 and 3.2. The methods of analysis are represented in Appendix A. Profiles 1 to 3 represent the study site (1) passing downslope to increasingly waterlogged areas (2 and 3).

The main feature of the results for the south facing slope is the high organic mater content of the middle slope soil profile, which decreases towards the foot of the slope into water logged soils. A further feature is the high proportion of sand down the profile and the fact that the principal difference in the horizons is the substantial amount of organic matter at the surface horizon compared with low amounts in the subsoil. As it was expected, in this type of soil, the reaction is acid due to strong leaching.

Table 3.1

Soil parameters

profile depth (cm)	particle size distribution % sand	silt	clay	% O.M.	pH in H2O	pH in CaCl2
Area A midslope profile 1						
0 - 7	54.81	24.58	20.61	22.40	5.19	4.76
7 - 31	62.84	23.41	13.75	6.50	4.29	4.00
31 - 70	68.30	21.81	9.89	0.51	4.21	4.05
+ 70	63.79	23.47	12.74	0.34	4.84	4.21
Area A profile 2						
0 - 20	67.22	15.88	16.90	7.97	5.05	4.73
20 - 55	65.20	21.73	13.07	0.38	5.82	5.43
55 - 82	65.87	23.43	10.70	0.64	5.74	5.32
Area A profile 3						
0 - 24	65.94	18.14	15.92	6.33	5.01	4.67
24 - 54	76.88	15.28	7.84	1.20	5.29	4.95
54 - 78	71.53	18.58	9.89	0.77	5.43	5.06
Area B midslope profile 1						
0 - 20	56.96	24.07	18.97	5.68	3.50	3.12
20 - 58	60.39	26.00	13.61	4.78	4.04	4.10
58 - 96	60.09	26.87	13.04	0.60	4.16	3.89
Area B profile 2						
0 - 17	36.65	35.26	25.09	24.13	4.16	3.93
17 - 31	59.65	28.27	12.08	8.95	4.55	4.16
31 - 43	71.98	18.95	9.07	4.09	4.35	3.56
43 - 90	56.00	27.98	16.02	4.17	4.55	4.04
Area B profile 3						
0 - 30	52.66	25.60	21.74	12.40	3.73	3.41
30 - 50	66.21	20.64	13.15	2.54	4.07	3.90
50 - 80	44.94	34.21	20.85	0.51	4.29	3.91

The pattern of exchangeable cations reflects the lower base status of the soils (Table 3.2). From Table 3.2 it is possible to visualize the effects of strong leaching although, as might be predicted, calcium accumulates towards the foot of the slope.

Table 3.2

Exchangeable bases (meq/100g of soil)

profile depth (cm)	Ca	Mg	K	Na
Area A mislope profile 1				
0 - 7	6.73	4.93	0.294	0.293
7 - 31	0.21	0.012	0.134	0.097
31 - 70	0.13	0.012	0.113	0.065
+ 70	2.14	1.23	0.095	0.143
Area A profile 2				
0 - 20	6.91	2.09	0.218	0.228
20 - 55	5.29	1.60	0.111	0.176
55 - 82	5.83	1.72	0.105	0.195
Area A profile 3				
0 - 24	5.20	1.72	0.155	0.176
24 - 54	4.21	1.04	0.047	0.143
54 - 78	5.20	1.97	0.067	0.156
Area B mislope profile 1				
0 - 20	0.088	0.012	0.264	0.143
20 - 58	0.044	0.012	0.147	0.097
58 - 96	0.044	0.012	0.201	0.123
Area B profile 2				
0 - 17	4.48	1.97	0.285	0.391
17 - 31	3.40	0.67	0.076	0.339
31 - 43	1.88	0.61	0.049	0.176
43 - 90	4.66	1.35	0.095	0.176
Area B profile 3				
0 - 30	0.34	0.012	0.187	0.130
30 - 50	0.13	0.012	0.092	0.084
50 - 80	0.62	0.246	0.138	0.110

Results of the soil analyses of the remaining profiles (north facing slope, Area B) are shown in the lower parts of the Tables 3.1 and 3.2. The sequence of the profiles is the same as for Area A. Profile 1 represents a well drained site in the mid of the slope and profiles 2 and 3 represent soil of poorly drained areas in the foot of the slope. High amount of sand, low pH levels (which result in weathering in strong acid conditions) and intense leaching of exchangeable bases are the main features of the three soil profiles on Area B. A major increase in the organic matter content occurs in the soils of the profiles 2 and 3. High levels of moisture prevail, subjecting these profiles to waterlogging, which result in anaerobic conditions and predominance of gleying processes.

3.6 Conclusion

Although the project was initially planned to be carried out on both valley sides, comparing grass covered with moorland sites, it had to be restricted to one side because of the problems related to permission and access and because of time limitations in setting the experimental sites.

In the end, the choice of the site was restricted to a mid-slope segment on the south facing slope because of:

1. The need for access through walking or by vehicle when transporting heavy equipment and materials

2. The added value of setting up site of interest to the hill farm managers at Boghall Farm

3. The desirability of selecting a site located in a well drained soil but, a priori, with the likelihood of being able to monitor both overland flow and subsurface flow.

Chapter Four

Methodology

4.1 Aim of the experimental methods

As stated earlier, the objective of the experiment reported in this thesis is to describe the variability of water flows over a hillslope segment of a small catchment.

This involved a comparison between three adjacent experimental plots, data from an adjoining reference plot and consideration of the errors in the various measurements made. Attempts were made to separate the flow components into lateral outflows from the soil horizons and vertical flows within the soil profile, in order to discover the most important type of fluxes in the study area. For such a study it was thought necessary to obtain data on:

- rainfall amounts
- evapotranspiration
- surface runoff
- lateral flow at horizon boundaries
- soil water content and its change at different depths
- soil water potential at different depths

This chapter describes the different procedures carried out to obtain the data outlined above and is divided in the following sections.

4.2 Setting up the experimental site

4.3 Runoff measurements

4.4 Precipitation measurements

4.5 Evapotranspiration

4.6 Soil water potential measurements

4.7 Soil water content measurements

7.8 Miscellaneous

4.2 Setting up the experimental site

The experiment was sited within a fenced area of 224m^2 on an even, sloping section of the south facing slope of Caerketton Hill at Boghall Farm. The locations of the raingauges, runoff plots, tensiometers nests and neutron probe acess tubes within the study area are shown in Fig.4.1, and details of one of the plots are shown in Fig. 4.2.

This section, first of all, reports the construction of the site and the installation of the equipment, discussing the problems encountered and the solutions adopted. This section then is followed by a discussion of the routine weekly measurements, problems encountered with the operation of the equipment during the two field seasons, measurement errors of the equipment and treatment of the results.

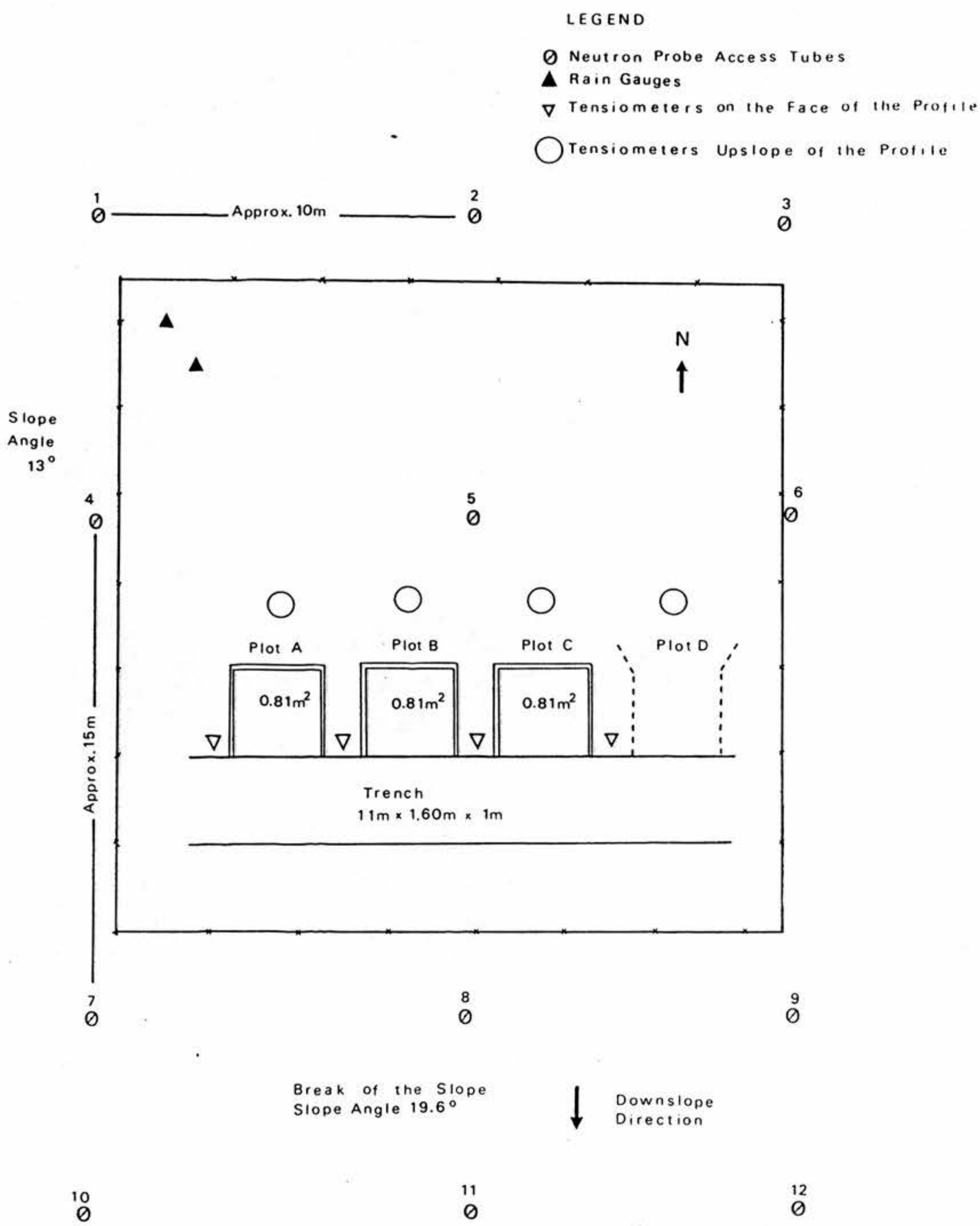


Fig. 4.1 Schematic diagram of the study area

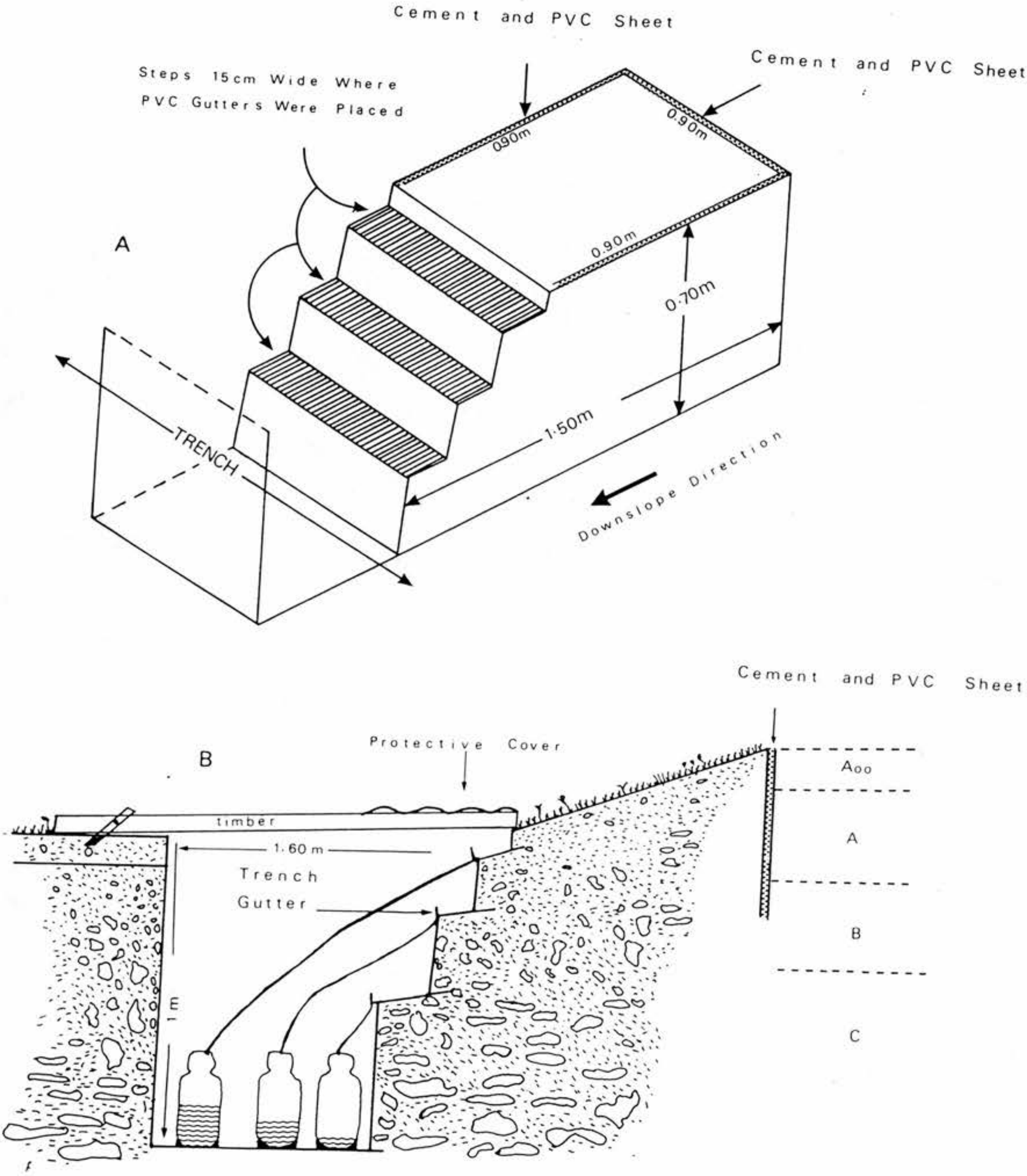


Fig. 4.2 Schematic diagram of one plot

4.2.1 Construction of the site and installation of the equipment

According to Atkinson (1978), the methods of measuring moisture on slopes fall into three categories:

(1) Methods involving interception of the flows

(2) Methods involving the addition of the tracers

(3) Indirect methods, such as the use of neutron probe and tensiometers.

In this experiment, methods 1 and 3 were used. The first involved the interception of the surface and lateral subsurface flows which were then channeled through plastic pipes into collecting drums. The aim of this equipment was to measure the volume of water draining laterally as saturated flow, to discover the types of flow and the conditions under which they ocurred and also to test the reliability of the method. The indirect methods employed involved the neutron probe for soil moisture content determination and tensiometers for determining the soil water potential. These methods will be described later.

The field techniques used to collect the flows from the exposed soil horizons are similar to those described by Whipkey (1965), Dunne and Black (1970), Weyman (1970; 1974) and Knapp (1973; 1974).

At first a trench measuring 11m long by 1.60m wide and 1.00m deep was excavated by a mechanical excavator within the study site (Fig.4.1). From the exposed face, three adjacent plots of 1.50m length by 0.90m in width and 0.70m depth were constructed. In the present research, owing to the labour involved in the excavation of the site, the transport of heavy equipment and materials uphill, and the difficulty of controlling larger experiments single handed, it was decided to concentrate on small plots. In deciding the area of an appropriate experimental plot to measure hydrological components efficiently, there is no clear consensus in the literature. Various plot areas have been used, ranging from $0.60cm^2$ to hundreds of squares meters (Arend and Horton, 1942; Amerman and Mcguiness, 1967; Anderson et al., 1984; Gurnell et al., 1984) and all were reported as giving plausible results. In this project, as the construction of large plots was impracticable, it was necessary to assume that the components of the hydrological cycle operated within the chosen plot boundaries as they appear to do for large plot areas. The basis for this assumption was derived mainly from reliable results obtained by Baloutsos (1985),who worked in a nearby area with plots of similar size. Also, the choice of 0.90m width was re-inforced by the availability of PVC gutters which saved in equipment costs. The gaps which were created by separating the plots from the surrouding soil were filled with cement, using a 5mm PVC sheet to act as a shield to prevent the cement from running off the plot sides and to ensure a cement layer of about 5cm thick. A thinner cement layer was impracticable, due to the presence of many stones in the soil causing irregularities in the plot sides. It was found that a thinner skin of cement would not adhere properly. It was also thought that a thinner cement layer would crack more easily due to freezing of the soil and from root action, especially within the top 25cm, causing water to enter or leak from the plots to the surrounding soil. A 5cm thick cement layer was therefore judged to be adequate to serve as a boundary, isolating the plot from the surrounding soil, although it demanded the use of approximately 300kg of cement for all the three plots. The gap between the PVC sheet and the surrounding soil was back -filled with soil. This procedure ensured that each plot was constructed as a discrete monolith isolated from the surrounding soil except at the base. When instrumented, it was hoped that such a field method would provide replicate plots with the structure of each soil pore space, in general, undisturbed within each monolith.

The three plots were constructed 1.5m apart(Fig. 4.1). The free face of each plot was stepped (Fig. 4.2) to support PVC gutters (92cm long X 21cm wide) inserted in the soil at the boundaries of the pedogenic horizons in order to collect water seeping from the free face.

It was expected that flows would build up just above an impeding soil layer, as pointed out by Kirkby (1978). It was also expected that, at the free face of the plots, due to the break in hydraulic continuity, the quantity of lateral flows would be reduced and water would concentrate upslope from the exposed face (Atkinson, op.cit). In an attempt to overcome this, the gutters were partially filled with a thin layer of soil to ensure a good hydraulic contact between the guttering and the soil face. Also, in order to ensure the separation of flows from each horizon a layer of plastic sheet was inserted into the free face at the horizon boundary, and this sheet was inserted as shown in Fig. 4.3.

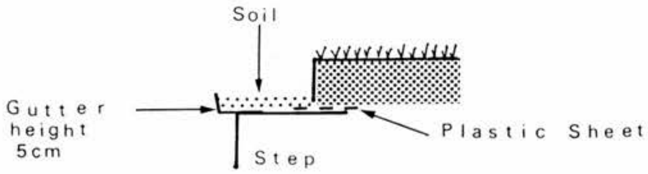


Fig. 4.3 Schematic representation of the gutter and plastic sheet inserted in the soil

To ensure that only water seeping from the soil horizons was being collected, the plots had securely battened covers of zinc protecting the gutters against the rain.

The area of the plots open to rainfall input after cutting the soil and inserting the first gutter, was 0.81m. The lower gutters drained areas of 0.99m and 1.35m respectively.

A further set of gutters was installed in the free face of the trench, 1.5m apart from the three bounded plots (Fig. 4.1), without artificial boundaries. This freely drained plot was intended to act as a control plot to indicate the total flows likely to occur over the plots in unrestrained conditions. The meaning of the term control is the same used by Cochran and Cox (1957), i.e. a treatment in which we are not particularly interested, but which may be needed in order to reveal, by comparison, whether other treatments are effective. In this project, the term treatment denotes the bounded plots, whose effects are to be measured and compared. The need for a control plot was governed by the assumption that the methodology employed is generally adequate for measuring flows over a hillslope but, occasionally, the conditions of the test are such that it is not. For example, the construction of the bounded plots resulted in their isolation from the surrounding soil and this could disturb both the temporal pattern and quantities of flows. In this case, the control plot served to reveal the actual temporal pattern and flow quantities and provided a check on whether or not the bounded plots were working.

The results obtained from the control plot had a very similar temporal pattern when compared with the results of the three bounded plots. Thus, in a broad manner, they did reveal that the bounded plots worked properly. However, difficulties in delimiting the catchment area of the control plot made direct comparison of the measured runoff values with the other plots impracticable. Therefore, the results of the control plot were only used in a qualitative manner, when necessary, in the analysis which is presented later in Chapter Five. The actual results of the control plot are fully detailed in Appendix B.

It was recognized that the results of the experimental plots were affected by errors from different sources. First of all, there were errors due to the actual technique of measuring the outflows from the soil. The construction of the plots implied a break in the soil hydraulic continuity. Also, there were errors arising from the natural soil variability (for example, soil permeability) and the accidental action of burrowing animals. Measures to prevent this type of disturbance included fencing the area and laying a wire mesh on the exposed face of the plots. This last procedure however, proved to be unworkable as fixing the wire mesh disturbed the soil profile. This was aggravated by the need to remove the mesh to adjust and clean the gutters.

As three replications of the plots were made, it was hoped that natural variability would be controlled by becoming proportionally distributed over all the plots. However, in the case of experimental plots, if a considerable number of enviromental factors are contributing to their variability, each of the factors must be proportionally distributed across the range of the plots outflow, otherwise a spurious result could appear (Church, 1984). In the case of this study however, it was possible to assume that the experimental plots were reasonably homogeneous, with respect to extraneous factors due to their close proximity; all the plots were at the same altitude and on similar angle of slope, in the same type of soil and under the same vegetation community and density. Thus any results, although including a degree of variability, could hopefully be considered to be valid, as will be demonstrated later in Chapter Five.

Simultaneously, along with the construction of the experimental plots, a network of access tubes was installed at the study site for neutron probe operation. Aluminium access tubes of 44.5mm outside diameter, 41.25mm inside diameter and 1.6mm wall thickness, closed at the bottom, were installed according to the recomendations of Eeles (1969).

As a general principle, due to the spatial variability of the soil texture and structure, it is advisible to set up an experimental project with the maximum possible network of access tubes that can be monitored in the available time.

A previous reconnaissance soil survey of the study area (see Chapter Three), allowed the experiment to be sited in an area with little variation in soil texture (see Table 3.1). Thus, considering the characteristics of the site and the number of measurements that were practicable to take in one working day, a network of twelve access tubes was installed at the study site, in a matrix of 4X3 (Fig. 4.1). The top of each access tube was closed by a rubber bung to avoid water entering inside the tube. The average height of the tubes above the ground was not less than 5cm.

At this stage, having excavated the trench and constructed the experimental plots and installed the access tubes network, raingauges and tensiometers were installed, as shown in Fig. 4.1.

Inside the experimental area, the precipitation was measured by means of two different raingauges installed approximately 1.5m apart (Fig. 4.1). One was a Casella natural siphon rainfall recorder supplied with a clock for weekly readings and the other was a British standard non-recording raingauge.

The two raingauges were liable to local errors mainly caused by the effects of the wind, producing turbulent eddies around the gauges, as pointed out by Bruce and Clarke (1980). As the study site was in an extremely exposed location and, because in most conditions, wind speed increases with the height above the ground, a number of measures were taken to avoid wind disturbance and splashing effects. The non-recording raingauge was installed with its rim at ground level in a pit, protected by a honeycomb PVC grid. The recording raingauge, with its rim approximately 30cm above ground level, was protected by a turf wall as described in Shaw (1983).

The next step in the instrumentation of the study site was the installation of the tensiometers.

The objective of installing tensiometers was to determine the direction of water flows within the soil profile. To accomplish this, mercury manometer tensiometers were installed in the exposed free face, and also 2.5m upslope of the plots in an undisturbed area. The tensiometers were installed as replicates at each depth, in an attempt to assess the variability of the soil water potential.

A second, but extremely important objective, in the installation at the tensiometers in the free face and also upslope of the plots, was to enable direct measurements to be made of the degree of disturbance to the soil water regime caused by the presence of the free face. This was considered necessary because of the observation of authors such as Knapp (1973) and Atkinson (1978), who pointed out that the construction of a trench to expose the soil face is likely to cause disturbances in the soil water regime. For example, the disturbance could inhibit the flow from the free face and also distort the pattern of water potential over the slope. The evaluation of such disturbances could be made by comparing the matric potential measured from both locations throughout both field seasons.

The tensiometers used in this experiment were already available from the Soil Science Department of the Edinburgh School of Agriculture and were of the type described by Webster (1963). The arrangement of the six tensiometer units used in this project was similar to the one depicted in Fig. 4.4.

Four nests of six tensiometers each, were installed in the exposed face of the pit close to the plots (Fig. 4.1 earlier). Duplicate tensiometers were inserted by augering nearly horizontally at a slight downward angle, at the mid point of each horizon as determined by the depth of the gutters installed. Thus, the depths of the tensiometers in the free face were at 10, 25 and 50cm, below the soil surface and the tensiometers penetrated the soil for approximately 6cm.

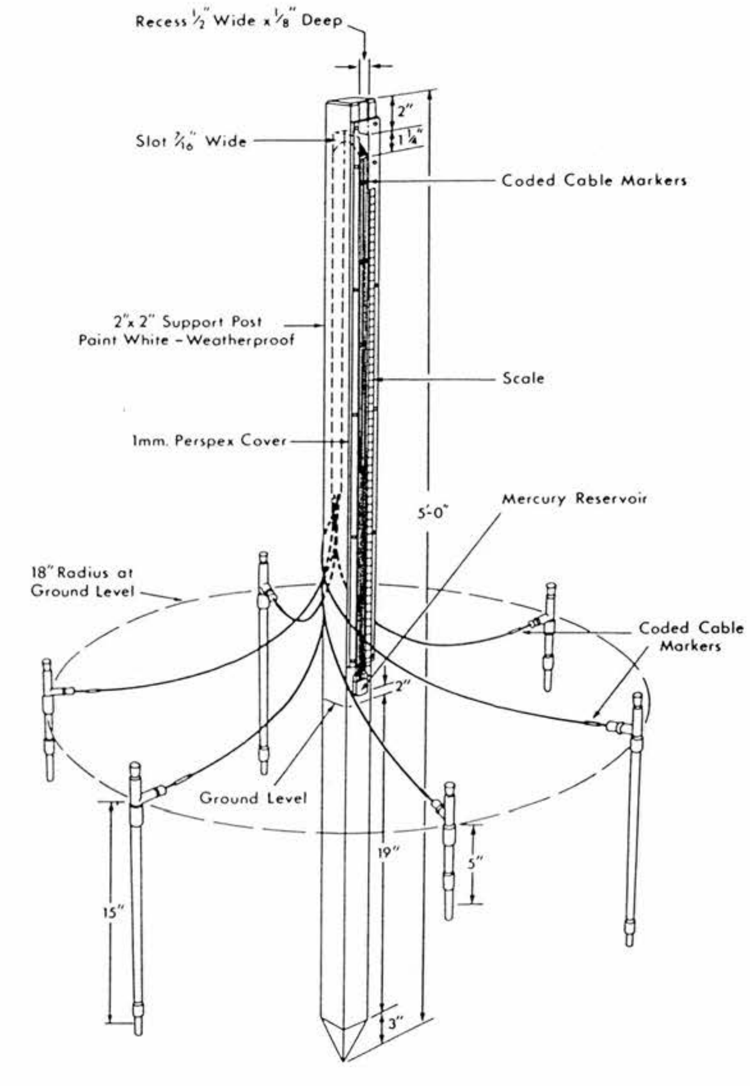


Fig. 4.4 Arrangement of a six cell tensiometer unit (after Webster, 1963)

The installation of the tensiometers in the free face suffered from some constraints. For example, it was difficult, due to the presence of stones in the profile, to insert the tensiometers at a definite depth. Also, after installation, the tensiometer suffered from the impact of driving rain, from freezing and thawing and also from snow setting off small 'avalanches' on the exposed face, all of which could loosen the soil around the face. These difficulties demanded the constant care and frequent re-insertion of the tensiometers in the free face of the pit. For tensiometers which were penetrating very stony parts of the horizons, a backfill of bentonite was used after the insertion of the tensiometer, to ensure a good hydraulic contact between the porous cup and the soil.

A further set of four nests, with five tensiometers each, was installed behind each plot at the distance of 2.5m (Fig. 4.1 earlier). These tensiometers were installed by augering a hole vertically into the soil, at 10, 20, 30, 40 and 50cm depth.

After installation, the tensiometers were filled with de-aired distilled water and purged in order to remove any air trapped within the system.

The construction of the study site was complete with the installation of the tensiometers. The next sections will report, and discuss, the weekly routine of measurements, problems encountered with the operation of the equipment, errors and treatment of the results.

It will be apparent that the upslope tensiometers were placed in a depth of 20cm, whereas the free face tensiometers were installed to a 25cm depth. This difference may result in difficulties in making significant comparisons, however the problem was unavoidable due to the presence of many stones in the soil.

4.3 Runoff measurements

The term runoff, in this thesis, is used in the sense of surface and immediate subsurface lateral flow from the soil profile.

The volumes of the flows from each horizon at each plot were collected at least weekly, and occasionally after a significant storm event, further measurements were carried out. During the routine measurements and inspection of the guttering system, it was suspected that occasionally, leaks did occur mainly on account of the stone content of the soil which made the proper insertion of the gutters and plastic sheets in the soil horizons difficult. If a leak was suspected the gutters were removed, cleaned and then re-inserted into the profile face. One of the three plots (plot A in Fig. 4.1) had leaks from its top gutter which were controlled by the this procedure. No significant leaks occurred with the other plots.

4.4 Precipitation measurements

Precipitation measurements were also carried out at least weekly, over the period of the experiment, except during snowy conditions during which there was the problem of obtaining meaningful readings.

Unfortunately, due to faults with the syphon gauge, a complete set of reliable records of rainfall intensity was not available. During the whole period of observation, i.e. 72 weeks, there were 23 weeks in which the automatic gauge had either partial or complete failures. Thus only 49 weeks of data were available and these will only be used to give broad picture of the rainfall intensity and duration in the study site during the period of observation.

Fortunately data on rainfall intensity was provided by the Departement of Meteorology of the University of Edinburgh, located approximately 5 miles from the study site. This rainfall intensity data was obtained from a rooftop site and will only be used when considering heavy storm events as an indication of the rainfall intensities that might have occurred in the study site.

During the water balance analysis, the rainfall data will be assumed to have an accuracy of ±20%, following the recommendation of Rodda (1969).

4.5 Evapotranspiration

Evapotranspiration estimates were not obtained from local metereological data. They were obtained from MORECS (Metereological Office Rainfall and Evaporation Calculation System) on a weekly basis, for the two observation periods (field seasons of 1984 and 1985). The estimates used were those for grid square 57, which encloses the study site (Fig. 4.5).

The reliability of MORECS estimates was qualitatively checked by considering the soil water balance and the hydraulic potential gradients. In most of the cases this gave satisfactory explanation for the evapotranspiration figures, as the direction of the flows of water in the

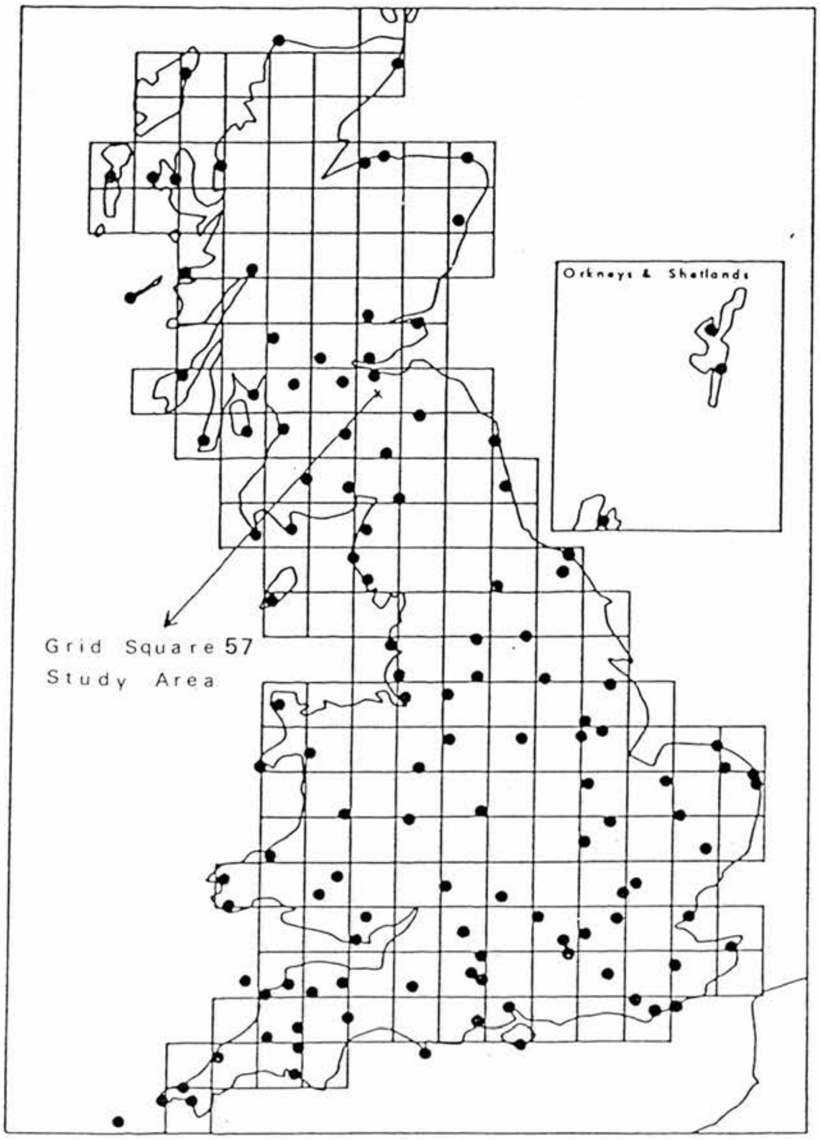


Fig. 4.5 MORECS grid squares and location of synoptic stations

profile was predominantly upwards in the summer and predominantly downward in the autumn/winter respectively, showing the depletion and surplus of the soil water. MORECS evapotranspiration estimates were used to calculate the drainage component at the bottom of the profile. Also by comparing this figure with the hydraulic potential gradients, and by considering its magnitude, it was possible to assess whether the evapotranspiration estimates were reasonable.

4.5.1 Error estimates of potential evapotranspiration (PE) and actual evapotranspiration (AE) calculated by MORECS

MORECS Et figures are reported in the literature to overestimate actual AE (Davies, 1981) but it was not possible to find any reference dealing with them for catchments in southeast Scotland. Further, the AE estimates are problematic, since they are derived from converted PE estimates, according to the degree of soil moisture depletion, which has an error of ±10% (Ward, op.cit). In addition the AE estimates produced by MORECS are calculated to represent a grid square of 40X40km. A description of the calculation of AE estimates is given by Thompson (1981).

Therefore the use of such generalised estimates demanded the acceptance of the above constraints and also the possible error of ±10% in PE estimates. However it has to be questioned whether the use of Et data, calculated for grid squares of 40X40km, can be applied meaningfully to an area of $224m^2$. In a general manner, the MORECS AE figures for the grid square 57 (Fig. 4.5) are in reasonable agreement with the values for summer evaporation of 3mm/day reported by Francis (op.cit) for agricultural upland areas in southeast Scotland.

The comparison between the MORECS estimates and the calculated hydraulic potentials aimed to check whether these estimates were following the evaporative demand

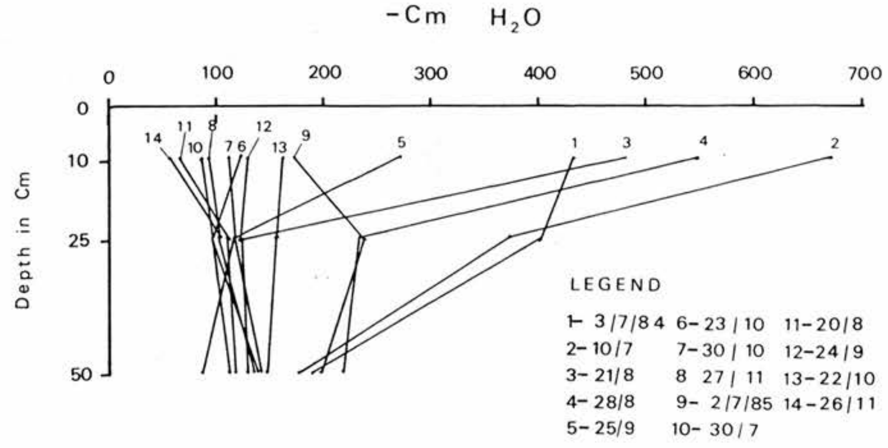


Fig. 4.6 Hydraulic potentials for selected weeks in 1984 and 1985

throughout the year. Fig. 4.6 is an example for selected weeks in 1984 and 1985, showing how the verification of AE figures was made. The hydraulic potentials were plotted for the dry and wet periods of 1984 and 1985. The determined directions of flows of water were initially compared with AE values for weeks in July and August 1984. Thus, as indicated by week numbers 1 to 4 in Fig. 4.6, water had been extracted from the soil and evaporated. The actual evapotranspiration figures from MORECS for those weeks, reflected this depletion of soil water and the shorfall of AE below PE also revealed that the soil was at moisture deficit (Fig.4.7).

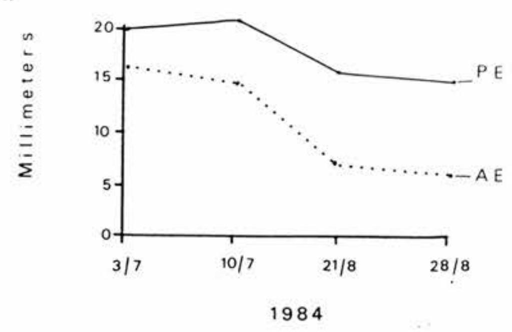


Fig. 4.7 Selected PE and AE values (July and August)

In September, October and November 1984 (Fig.4.6 weeks numbers 5 to 8) when the soil became wet, it was possible to identify the change of seasons (summer to autunm), which meant that an adequate supply of soil water was available, enabling evapotranspiration to occur at the full potential rate. This can be seen in Fig.4.8:

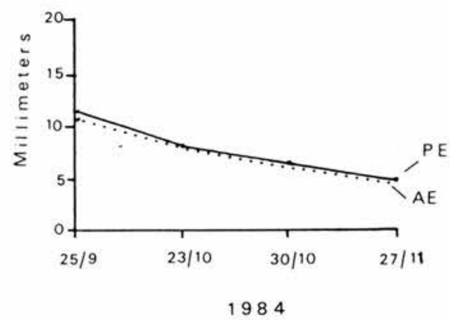


Fig. 4.8 Selected PE and AE values (September to November)

During the summer and autumn of 1985, there was an adequate supply of soil water on most occasions as can be inferred from weeks 9 to 14 in Fig.4.6. Reflecting this surplus of soil water, AE occurred at its full potential rate, obviously decreasing in the autumn as the evaporative demand fell, as shown Fig. 4.9.

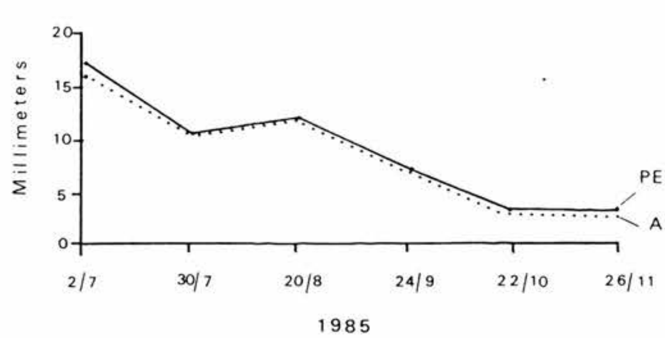


Fig. 4.9 Selected PE and AE values (July to November)

This procedure of checking AE values, using flow direction and water potentials, was carried out for each week during both field seasons. In general, it proved to be a reliable procedure as it gave evidence that AE figures obtained from MORECS were, despite their error component, following the evaporative demand of the seasons and the supply rate of the soil. This enables them to be acceptable for use in studies of the water balance at the research site.

4.6 Soil water potential measurements

4.6.1 Working principles of the tensiometers

A tensiometer consists of a porous cup, generally of ceramic material, filled with de-aired water and connected through a tube to a manometer. The porous ceramic cup is necessary to ensure a continuous film of water from the soil to the tensiometer. As the porous cup is inserted in the soil, the water inside the cup comes into contact and tends to equilibrate with the soil solution through the pores in the ceramic wall. As the soil water is usually at subatmospheric pressure it exerts a suction which pulls the water from the tensiometer which is at atmospheric pressure, lowering its hydrostatic pressure. Thus, the variations in the pressure, as a result of wetting and drying the soil, are indicated by the height of the mercury column in the manometer.

The range of the matrix potential which can be measured by a tensiometer is generally limited to values below 1 ATM (less than 0.85 bar). This may happen because the ceramic material is very permeable and porous; too much suction may cause air entry into the cup equalizing the internal pressure to the atmosphere. Soil suction will continue to increase under these conditions, but the tensiometer will fail to show it (Hillel, 1982).

As pointed out earlier, the tensiometer indicates the variations of the soil matric potential by the rise and fall of its mercury column. From Naysmith (1979), the calculation of the matric potential can be summarized as:

$$\psi_m = H - 12.6 - Q \qquad (4.1)$$

$$\psi_h = \psi_m - D \qquad (4.2)$$

Considering the soil surface as a reference level and

ψ_m = matric potential

ψ_h = hydraulic potential

H = distance from the top of mercury reservoir to the porous cup in cm

h = height of the mercury column

D = distance from the soil surface

Q = capilary depression correction factor in cm of H_2O, given by the expression $Q = 11.8 / D$, where D is the internal diameterofthe nylon tubing, which is in this case 1.5mm, making Q = 7.86

4.6.2 Routine of tensiometer readings and treatment of the results

Readings of the tensiometers were also made at least weekly, and occasionally after significant storm events further readings were made. During the summer, these readings were interrupted in some weeks when the soil was at low potentials beyond the range of tensiometers (i.e. less than - 0.85 bar). During the winter, readings were also interrupted due to snow and freezing of the soil as already mentioned. During the entire period of observation the tensiometers were checked for blockages and purged with de-aired water when necessary.

As pointed out by Naysmith (1979) the large variability encountered when measuring matric potential, demands the average of several tensiometers readings to give acceptable results. Webster (1966), suggests the use of the geometric mean as a technique to overcome the inherent large variability of tensiometer data. The advantage of using the geometric mean is that it gives a more typical average than the simple arithmetic mean, since it is less affected by extreme values (Arkin and Colton, 1964).Therefore the geometric mean of the tensiometer data was calculated and its standard deviation was obtained following procedures adopted by Naysmith (op.cit).

4.7 Soil water content measurements

Considering the long term nature of this project, and the importance of obtaining accurate measurements for the changing soil water content within the experimental area, a neutron probe was used to estimate the soil water content.

This method for measuring water content, although it has some limitations, has great advantages compared with other methods. The neutron probe method has the advantage of being nondestructive of the experimental soil environment, less laborious and more rapid than other techniques (eg. gravimetric method) and permits repetitive measurements of soil water content in the same relatively undisturbed soil over long periods of time. However, care needs to be taken when using the instrument both to avoid any radiation hazard and also to obtain accurate readings. Also, for accurate results, a calibration curve for each soil is essential.

In view of the importance of the soil water data obtained by this method to the overall project, it is important to understand the operating principles and limitations of the neutron probe. Thus, in the next sections, the theory of the neutron probe, obtaining a calibration curve, the routine use of the neutron probe, and the error of the measurements will be considered in some detail.

4.7.1 Theory of the neutron probe

The neutron probe used in this research was the Wallingford Soil Moisture Probe, as described by Bell (1976), with an Americium-Berylium neutron source. Americium-Berylium is used in such probes partly on grounds of safety, and partly because this material has a very long half-life (450 years) reducing any probleem of drift due to loss of activity.

The in situ measurements of soil moisture that can be obtained with the neutron probe are based on the marked property of hydrogen nuclei in the soil water for scattering and slowing neutrons. In practice, most soil elements have a low ability for scattering and slowing neutrons, influencing the count rate measured in the probe. However, the hydrogen nuclei, including that of bound water and organic material, exert the principal effect on the count rate.

When the probe is lowered into the soil, the high energy neutrons emitted from the radioactive source are slowed and changed in direction by elastic collisions with the nuclei of the soil atoms, predominantly those of hydrogen in soil water (Gardner, 1965; Bell, 1976). This process of slowing neutrons to thermal energy level of atoms in a substance at room temperature (thermalization) allows the neutrons to be absorbed by other nuclear reactions. After the collisions, a cloud of slow neutrons, whose density is largely a function of the soil water content, is generated and then sampled by a slow neutron detector (in general boron-trifluoride) inside the probe (Bell, op.cit). The slow neutron detector generates electrical pulses which are initially amplified and 'shaped' before being displayed as a mean count rate in the counter unit. These count rates can then be translated into the volumetric moisture content of the soil by means of an appropriate calibration curve. In general the calibration curve is obtained by regressing the neutron probe count rate ratio (the ratio of count rates obtained in the field with a count rate obtained in a drum of water) on the volumetric water content obtained independently. The ratio calibration method is effective because it ensures continuity of records and corrects distortions due to the following causes (Bell, op.cit; Hanks and Ashcroft, 1980):

1- The different sensivity after probe failure and repair

2 - Decay of the source strength

3- If more than one probe is in use, because no two probes have the exactly same count rate.

4.7.2 Calibration methods

There are three main methods of obtaining a calibration curve for the neutron probe: (1) theoretical calibration; (2) drum calibration and (3) field calibration. These methods are described in Bell (op.cit) and Ølgaard (1965). In this project, the field calibration method was used as it was not possible to use theoretical calibration, due to its cost, and it was impracticable to remove enough soil (approximatly four or five tons of soil) from the study site for drum calibration.

The procedures for collecting soil samples at the study site, and the calculation of the calibration curves, followed the recommendations of Greacen (1981). The calibration curves obtained expressed the functional relationship between the volumetric water content (θ) and the neutron probe count rate ratio N / N_w, in a linear form:

$$\theta = b\,N / N_w + a \qquad (4.3)$$

where b is the calibration coefficient

N is the count rate in the field

Nw is the count rate in pure water

a is the intercept constant.

As mentioned earlier, the neutron probe method has limitations, and one of them is related to the difficulty of obtaining reliable readings close to the surface. Acccording to Bell (op.cit) this happens because the density of the 'cloud' of slow neutrons is affected by the probe approaching the surface where there is a loss of fast and slow neutrons from the soil system. In an attempt to overcome this difficulty, application of separate calibration curves for specific depths in the surface zone was made. The variable N in the above equation was corrected for bulk density variations; Greacen and Schrale (1976) and Grant's (1975) surface correction factors were included to obtain curves for 5 and 10cm depth readings. The following were the calibration equations obtained for this project:

$$\theta = 64.94\,N/N_w + 8.88 \quad \text{for 5cm depth} \qquad (4.4)$$

$$\theta = 45.74\,N/N_w + 7.585 \quad \text{for 10cm depth} \qquad (4.5)$$

$$\theta = 46.89\,N/N_w + 4.04 \quad \text{for depths greater or equal 20cm} \qquad (4.6)$$

4.7.3 Routine use of the neutron probe

In principle, the readings in the field were carried out every week. However, during prolonged dry spells in 1984, when little variation in the soil moisture content was expected, the readings were taken at intervals of 15 days. In the field season of 1985, as there was already a considerable amount of data available, it was decided to take routine readings at intervals of 15 days, and to take extra readings as required when significant changes could be expected to occur, for example during wet periods of the summer.

Before and after using the probe, a series of five counts of 64 seconds were taken in a drum of water. These readings were to check for any drifts or abnormalities in the instrument and also used in the calculation of the calibration curve as the equation is based on the count ratio.

After setting the probe on an access tube, the source was then lowered down through the profile and readings were taken at 5, 10, 20, 30, 40, 50 and 60cm depths. This spacing of readings was based on the fact that effective radius of the neutron probe in measuring the changes in moisture content is 15cm in wet soil and up to 30cm in very dry soil. This implies that the indicated moisture value is the mean for a sphere of that radius centered on the measuring point. Therefore 10-15cm is the optimum spacing for reading and no greater resolution can be obtained by decreasing this figure (Bell, op.cit). The time of each measurements was 16 seconds, a reasonable count time to obtain an acceptable count precision (Greacen, op.cit).

The neutron probe data was processed using a computer program developed by Naysmith (1984), designed to calculate the volumetric soil moisture content. Basically the program considers the data from the access tubes as three replicates for each four treatment rows and calculates the mean volumetric water content and coefficient of variation for each row at each depth. The program then calculates the equivalent depth of water (in millimeters) in each layer and summed for the whole profile, the change in water content in each layer and for the whole profile and the cumulative change in water content during the season.

To obtain the soil water content, the program uses the linear calibration equations relating volumetric moisture as a function of the neutron probe count rate given earlier.

4.7.4 Estimate of the error component in the measurement of the change in water content

In this project, the accuracy of the total water estimates was not considered in detail, since the main interest of the analysis is in the changes of the soil water content. The procedure for estimating the error involved in the change in water content between consecutive dates, followed the recommendations of Sinclair and Williams (1979) and was calculated as follows:

$$S^2(\Delta\bar{\theta}) = b^2 S^2(\Delta\bar{n}) + (\Delta\bar{n})^2 S^2(b^2) - S^2(\Delta\bar{n})\, S^2(b^2) \qquad (4.7)$$

where,

$S^2(\Delta\bar{\theta})$ is the variance of the change in water content

$\bar{n}$ is the mean count rate ratio, obtained from count rate ratios of field data with count rates in pure water

$S^2(b)$ is the variance of the coefficient of calibration

$S^2(\Delta\bar{n})$ is the variance of the difference of the mean count rate ratio between consecutives dates

b is the coefficient of the calibration equation.

Obtaining error estimates for each result down the soil profile, and for each observation date, would have involved a considerable amount of calculation. However, error estimates were obtained by considering typical extreme conditions and by concentrating on the surface (5, 10 and 20cm depth) result which were subjected to the greatest degree of variability. This can be verified from an examination of Fig. 5.9 (Soil moisture content versus time at each depth - in Chapter Five). As a consequence, the estimates of the error term, when applied to the whole soil profile, may slightly underestimate the true accuracy when estimating the change in soil water content.

In order to determine the variations in the estimate of the water content change at those depths ($S^2(\Delta\bar{\theta})$), the following times were chosen:

days: no 28 (08/5/84) and 70 (19/6/84)

days: no 112 (31/7/84) and 175 (02/10/84)

These periods were selected as they mark the largest changes in the soil water content and have a certain degree of independence. In other words it was thought that weekly changes in soil water would not be independent, since soil water value which is high in one week would probably be high in the following week.

The data set for 1984 was therefore divided to show variations within the spring and early summer, and variations within late summer and early autumn. This avoided having an error figure for very similar conditions either within a season or between times when soil was at field capacity. The error figures obtained were also assumed to be representative of the changes in water content which occurred during 1985.This assumption was required as during 1984 it was possible to calculate the error in the change of the water content under quite different soil water conditions. However, in 1985 this was not possible as only small variations in the water content occurred. This suggested that the error figures determined in 1984 may be more typical as they were determined from independent changes in soil water.

Tables 4.1 to 4.3 show details of the neutron probe data used in equation (4.7) to obtain estimates of the error component of the change in soil water content:

Table 4.1

Mean count rate ratio ($\bar{n}$), Standard deviation (S) for the study site at 5cm depth

day no.	$\bar{n}$	S
28	0.192	0.052
70	0.305	0.049
112	0.165	0.061
175	0.271	0.095

Table 4.2

Mean count rate ratio ($\bar{n}$), Standard deviation (S) for the study at 10cm depth

day no.	$\bar{n}$	S
28	0.250	0.053
70	0.297	0.038
112	0.152	0.023
175	0.243	0.072

Table 4.3

Mean count rate ratio ($\bar{n}$), standard deviation (S) for the study at 20cm depth

day no.	$\bar{n}$	S
28	0.318	0.051
70	0.319	0.062
112	0.182	0.062
175	0.235	0.072

A summary of the results obtained from the calculation of equation 4.7 is shown below.

Table 4.4

Error estimate of $\Delta\bar{\theta}$ for 5cm depth

day no.	mean water estimate (%)	$\Delta\bar{\theta}$ (%)	standard error of $\Delta\theta$ (mm)
28	15.66	-4.58	1.4
70	20.24		
112	14.81	-4.08	2.3
175	18.89		

Table 4.5

Error estimate of $\Delta\bar{\theta}$ for 10cm depth

day no.	mean water estimate (%)	$\Delta\bar{\theta}$ (%)	standard error of $\Delta\theta$ (mm)
28	14.62	-1.26	0.9
70	15.88		
112	12.01	-2.45	1.0
175	14.46		

Table 4.6

Error estimate of $\Delta\bar{\theta}$ for 20cm depth

day no,	mean water estimate (%)	$\Delta\bar{\theta}$ (%)	standard error of $\Delta\theta$ (mm)
28	20.19	0.37	1.0
70	19.82		
112	14.74	-2.02	1.3
175	16.76		

For the determination of the results shown in Tables 4.4 to 4.6, the mean water content of 3 access tube rows was used and the calibration coeffifients were from equations 4.4 to 4.6.

Examining the error estimates for the changes in water content, it is possible to see (Tables 4.4 to 4.6) that, as expected, large variations occurred close to the surface (between 5 to 20cm depths). At 5 cm depth, the large variation occurred in the second period (i.e. from days no. 112 to 175) whilst for 10cm and 20cm depth the variation was large during the first period (days no. 28 to 70).

Although it is not the objective of this section to find a straightforward answer for such variations, it is possible to attribute them to four sources:

1 - A local component related to the heterogeneity of the soil or even to its disturbance by grazing animals or people, since most of the access tubes are outside the fenced site and the area is used as a pasture and may be slightly disturbed.

2 - The slope, which makes estimates of the tube height difficult. This means that the surface of the soil could not be determined accurately

3 - Imprecise re-location of the probe. As pointed out by Bell(op.cit), an error in depth relocation as little as 1cm can cause significant errors in the measured water content

4 - A calibration component related to an imprecise calibration equation.

Finally, having calculated the error estimates of the changes in water content, it is necessary to assess the meaning of this error component when analysing the soil water balance. In particular it is useful to know what level of accuracy could be given to the estimated drainage component. The moisture content results had to be converted into millimeters of water. Then, the three representative values were added together for the whole profile, resulting in an assessment of ±2.7mm and ±3.1mm for the dry and wet periods respectively, as the accuracy of estimates for the drainage component.

The above results were in the same order as those reported by Sinclair and Williams (1979) and will be used in subsequent calculations in Chapter Five.

4.8 Miscellaneous

Data on soil dry bulk density was obtained by taking soil samples of known volume in the study site. This data was necessary for the calibration of the neutron probe. Also a soil moisture characteristic curve was obtained by using a tension tank and pressure tank with intact cores. These data were used in the determination of the water content at field capacity as will be shown later in Chapter Five.

Chapter Five

Results and Discussion

The field work described in the previous chapter generated a great deal of data and included rainfall and runoff amounts, soil water content and soil water potentials. Fig. 5.1 shows the periods over which data was collected during the two field seasons.

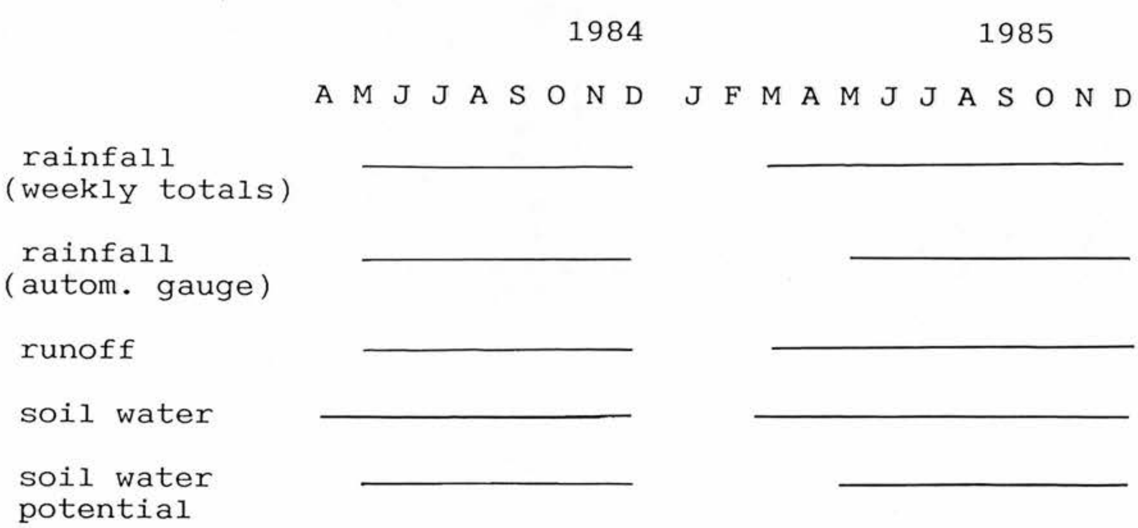


Fig. 5.1 Chronogram showing the periods of the measurements of hydrological and soil water components

In addition to data collected in the field, complementary measurements of soil physical properties such as bulk density and the soil moisture characteristic curve were determined in the laboratory.

In this chapter, a broad view of the results is given first of all in order to establish a framework for the discussion of detailed processes and properties in the next section. The data will be considered in the following order:

1 - General description of rainfall quantities, intensity and duration

2 - A summary of the temporal pattern of the runoff flows from each plot

3 - Runoff amounts for each gutter

4 - Variation between plots

5 - Calculation of the water balance on a preliminary monthly basis

6 - Analysis of the water balance, based on data collected weekly

5.1 Description of the rainfall quantities, intensity and duration

Table 5.1 shows the monthly rainfall measured at the study site (Boghall Glen) compared with the long term monthly averages 1941-70 which existed for Boghall Farm (data supplied by Meteorological Office).

Table 5.1

Monthly rainfall at the study site and its long term average (standard period 1941-70)

year/month	M	A	M	J	J	A	S	O	N	D
1984	*	*	47	53	28	21	91	79	209	58
1985	44	130	57	50	257	93	174	47	46	136
average (1941-70 Boghall Farm)	48	51	69	55	85	99	79	72	82	72

(millimetres)

* No data. Measurements began in May

For 1984, the first field season, examination of Table 5.1 shows that there were two very dry months, July and August, when rainfall was well below the average. These low rainfall amounts, when combined with the evaporative demand during the season, imply that a soil moisture deficit is likely to have occurred. During this period, as will be shown later, most of the soil water was lost by evapotranspiration; however, some lateral runoff and deep drainage did occur.

During September and October the rainfall was above average and was exceptionally high in November (when practically 50% of the monthly total fell in a period of 24 hours). During November, and particularly during the first week, the highest runoff amounts of the first field season were measured. In December, the rainfall decreased to below average and, although the soil was at field capacity, no runoff occurred, as will be shown later in this chapter.

The second field season, 1985,was far wetter than the first, especially in April, July, September and December (when again high rainfall amounts fell in periods of 24 hours). During these months, the amount of rainfall was also higher than the long-term average (Table 5.1).

Rainfall amounts well above average were also measured during April 1985. Unfortunately snow and ice made soil water potential measurements impractical from January to April. However, the soil was very wet and probably at field capacity leading to the conclusion that downward movements prevailed during these months.

From Table 5.1 it is possible to see the appearance of the so-called 'summer deluge' of 1985; both the July and September rainfall amounts were well above the average. August, although marginally below the average, was a wet month, not simply by the amount of rainfall but because there were only two rain-free days (data from Bush House).

These high rainfall amounts meant that the soil moisture deficit was much less than that of the previous summer, and in fact the soil returned to field capacity in July. However, as will be demonstrated later in this chapter, most of this rainfall was lost as deep drainage and not as lateral runoff. Rainfall decreased again in October and November (Table 5.1). However, as evapotranspiration was low during this period, the decrease did not bring about a soil moisture deficit. By December, the rainfall increased again above the average; however, very cold conditions restricted the measurements (soil water potential and soil water content) to the first week of the month.

This broad picture gives an idea about the rainfall quantities measured in the study site, as well as the significance of the dry and wet periods. The rainfall intensities and duration are shown next, as a complement to the general view of rainfall during the two observation periods (Table 5.2).

Table 5.2

Rainfall intensity-duration
(May-Dec 1984; May-Dec 1985)

Rainfall Intensity	Duration in hours																
mm	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.5	8.0	8.5	9.0	9.5
0.1 - 0.2	1	4		8	1	2		14		1	2	2					
0.3 - 0.4	1	1	1	1	2	1		1	1	2							1
0.5 - 0.6	1	14	2	5	1		1	2				1					
0.7 - 0.8	4	9		1		2	1	2	1				1	1		1	
0.9 - 1.0	7	7			1						1	1					
1.1 - 1.2	4	1		3			1	1	1						1		
1.3 - 1.4		2											1				
1.5 - 1.6	1	3		2	1	3		1	2								
1.7 - 1.8				3	1												
1.9 - 2.0	5	2	2	1													
2.1 - 2.2				1			1	1									
2.3 - 2.4			1														
2.5 - 2.6		1						1									
2.7 - 2.8					1												
2.9 - 3.0	1		1														
3.2 - 3.3			1														
3.4 - 3.5				1													
3.6 - 3.7				1	1												
3.9 - 4.0		1			3												
4.7 - 4.8			1														
4.9 - 5.0		1															
5.5 - 5.6		1															
5.9 - 6.0			1														
6.9 - 7.0	1	1															
9.0 - 9.1	1																

Note: numbers are the frequency of events

Table 5.2 shows the rainfall intensity duration at the study site based on the existing data from the rainfall recorder. As reported earlier, the rainfall recorder had failures, especially during the periods of heavy rainfall of November 1984, and in the months of July and September

1985. However, by the end of the whole observation period, it was possible to use the data set and obtain a reasonable picture of the rainfall intensity-duration at the site.

The data shown in Table 5.2 reveals that the majority of the rainfall events occurred as slight or moderate rain (not more than 0.5mm hr^{-1} and between 0.5 and 4.0mm hr^{-1}, respectively). Very few occurred as heavy rain. This information, added together with the data on Table 5.1, gives a broad picture of the rainfall in the study site and helps to understand the low amounts of runoff collected.

As shown earlier, this variation in the rainfall quantities meant that the first field season had in the 'summer' exceptionally dry conditions and in the 'autumn' (November) unusually wet conditions. The second year (1985) on the other hand had, for the same 'summer' period, unusually wet conditions. This variation made the results of this work particularly interesting as they represented data from two contrasting seasons and could therefore be presumed to compare extreme patterns in lateral and vertical soil water flows.

5.2 A summary of temporal patterns of the flows for each plot

The broad temporal pattern of the total plot runoff results is shown in Fig. 5.2, where it is possible to compare the measured rainfall and the total outflow from plots A, B and C.

The figure shows that the temporal pattern is quite

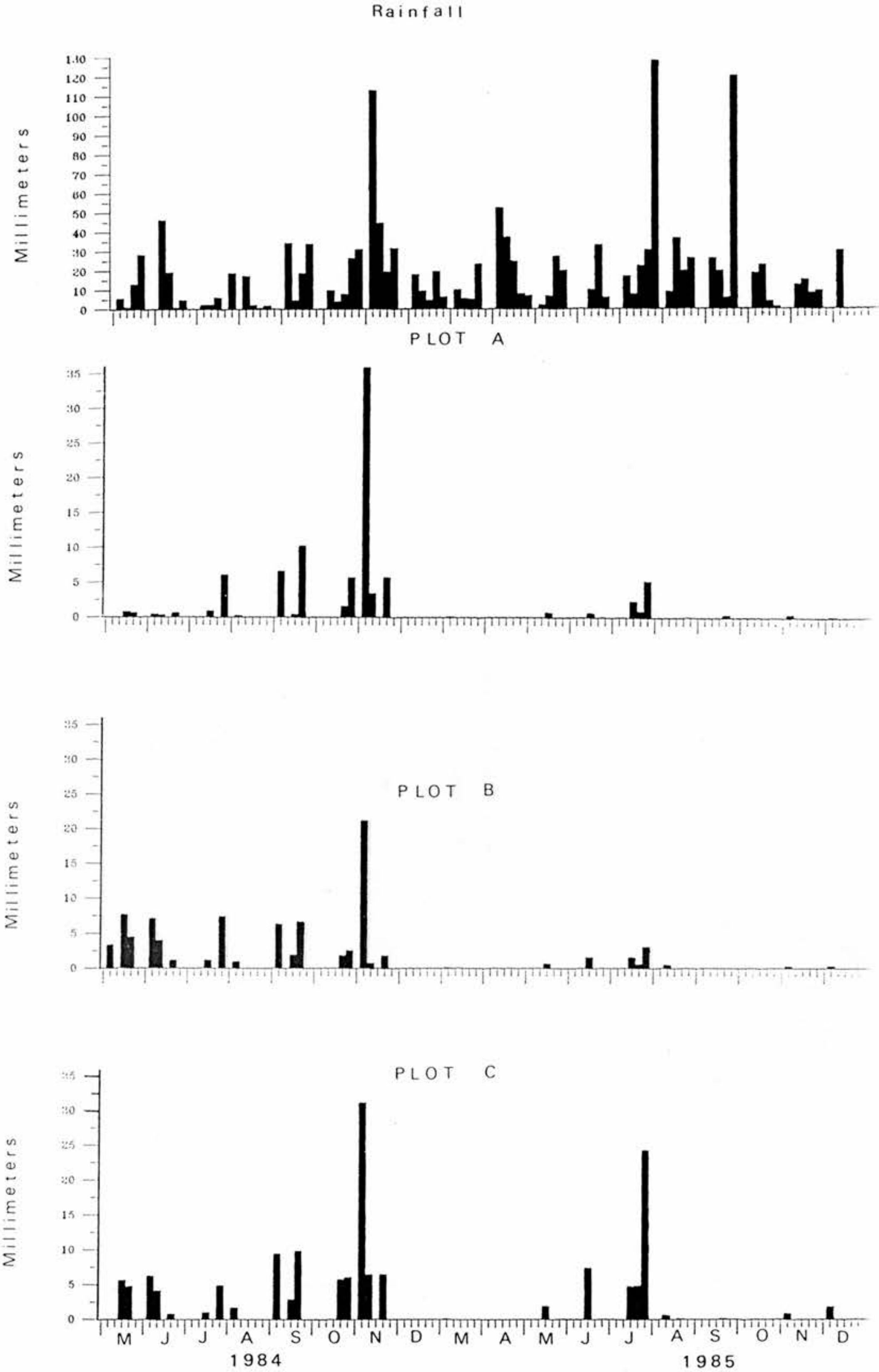


Fig. 5.2 Rainfall and total outflow from plots A, B and C

N.B. Rainfall at different scale for ease of presentation.

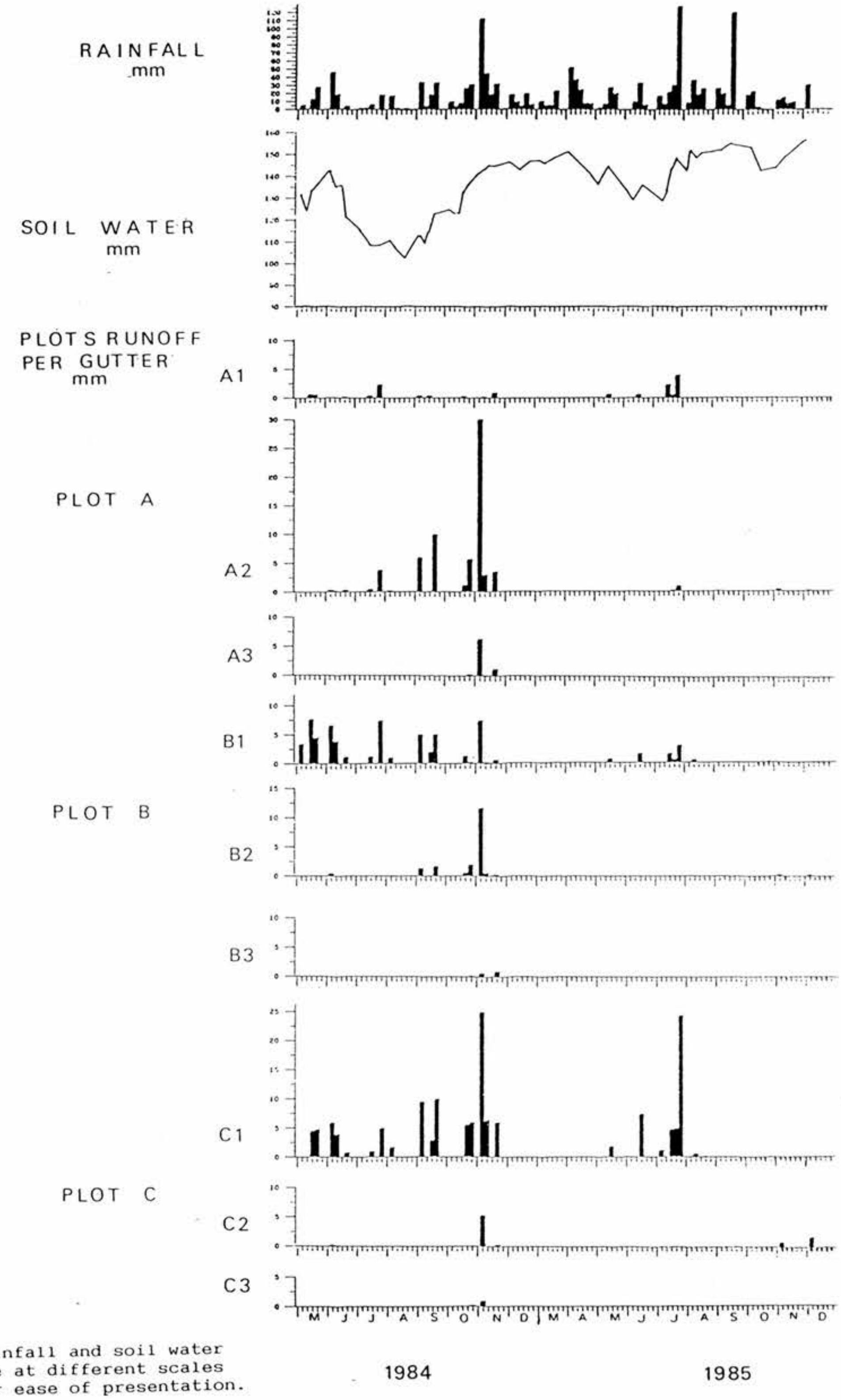
similar between plots, especially during the period which accumulated a high rainfall amount in the first field season, i.e. November 1984. Total runoff quantities obviously varied, especially in July 1985 when plot C collected a much higher runoff amount than the other two plots. The significance of these variations is discussed in a later section. It should also be noticed that runoff quantities were low in relation to rainfall, especially during the wet periods.

Comparing both field seasons it is possible to see that runoff quantities in all three plots, from May to September 1984, were higher than the same period in 1985 despite the higher rainfall amounts accumulated in this second period. This subject will be dealt with in more detail in the analysis of the weekly water balance.

An evaluation of these runoff quantities, based on the rainfall intensities (Table 5.2) observed during the two field seasons, permits the suggestion that the measured low amounts can be related to the low rainfall intensities, and to constant high matric potential in the soil profile, which will be shown later to be responsible for flows controlled by gravity.

5.3 Runoff amounts for each gutter

A more detailed illustration of the plot runoff is given in Fig 5.3, where flows are presented for each gutter during the two field seasons, compared with rainfall and



N.B. Rainfall and soil water
are at different scales
for ease of presentation.

Fig. 5.3 Rainfall, soil water and runoff per each gutter soil water content.

In Fig. 5.3 gutter A1 for example, collected surface and subsurface flows from the top soil horizon of plot 1 and gutter A2 and A3 collected the flows from the A and B soil horizons of plot 1, according to the procedures outlined in Chapter Four. The same order of flow collection is followed in the plots B and C.

From Fig. 5.3, it is possible to see that the soil water content at the begining of the experiment was close to 135mm. However, a decrease in the soil water content was noticeable in June, July and August, when the average value was close to 105mm. This behaviour of the soil water content reflects the dry conditions of the 1984 summer as shown in Table 5.1. Re-establishment of the moisture supply in the soil, following larger and more frequent amounts of rain, occured from mid-October (Table 5.1 and Fig. 5.3). Following the sequence of observations of soil water content until the end of the period, it is possible to notice that the water content remained almost constant, showing only a slight decrease in June and July 1985. This reflected the wet conditions of the summer 1985 (Table 5.1) which allowed the soil to be at or near field capacity for most of the time.

From the histograms shown in Fig. 5.3, it is possible to determine that, in general, the three gutters in each plot behaved in a similar temporal fashion.

Looking at the whole set of gutter data in Fig.5.3, it is possible to see that on most of occasions flows were coming from the top gutter. An exception to this pattern occured in plot A, where gutter A2 collected larger quantities of flows than gutter A1. This was evident in periods of heavy rain during the first field season and, in particular, after the storm which occurred in the week between 30/10 and 6/11/84. During this storm, the rainfall accumulated in 24 hours reached 81mm, with several rainfall intensity events of 8mm hr^{-1} (data on rainfall intensity from Meteorology Department of University of Edinburgh). The runoff collected after this 24 hours period is shown in Table 5.3.

Table 5.3

Runoff, in millimetres, collected in the plots
(24 hour period)

gutter	plot A	plot B	plot C
1	0.0	6.0	21.0
2	24.7	10.0	5.4
3	6.0	0.5	0.5
total	30.7	16.5	26.9

Given the considerable rainfall amounts measured in 24 hours, the flows collected in the three gutters of plots B and C are quite acceptable. However, it was surprising that gutter A1 had no flows especially as the plots were close replicates constructed in the same soil type, vegetation cover and angle of the slope.

Absence of flows in gutter A1 after this 24 hour period of rainfall gave rise to the suspicion that a leak had occurred from gutter A1 to gutter A2, thus implying an overestimation of the runoff amount from A2. Although the gutters were checked regularly for leaks (by means of removing and cleaning them as reported in Chapter Four), the efficiency of the uppermost gutter of plot A is questionable during periods of heavy rain in the first field season. Better performance of gutter A1 was obtained, after removing stones re-inserting and ensuring that the gutter remained fixed in its soil layers, throughout 1985.

Table 5.4 shows details of the number of times that flows were measured in each gutter.

Table 5.4

Number of times flows were measured in each gutter (72 weeks of observation)

gutter	plot A	plot B	plot C
1	19	25	27
2	15	8	4
3	4	3	2

From Fig. 5.3 and Table 5.4 the indication is that most flows occurred as surface and subsurface flow, especially when examining plots B and C and after making allowances for the possible overestimation of the number of flows collected in gutter A2. Turning to the lower gutters, it is possible to see that the amounts collected were slight and only occurred on a limited number of occasions. Considering the period when there was a decrease in rainfall and soil water content ('summer' 1984), the occurrence of flows in the uppermost gutters was the result of rainfall on a dry soil obeying the pattern exemplified in Brady (op.cit) and discussed earlier in Chapter Two. In relation to the lower gutters, low amounts and frequencies of flows can be explained by the low matric potentials present in the soil in the dry period, and high and constant matric potential in the wet period, which prevented the occurrence of lateral flows.

Examining the broad picture (Fig. 5.2 and 5.3) of rainfall and water flows, especially during the wet periods of the two field seasons, it is apparent that the amounts of water collected by the gutters were only a small proportion of the total rainfall. Thus, it would appear that, as a first proposition, water passed vertically through the soil profile. Discussion of this idea will be presented in later sections of this chapter.

During late October and early November 1984, all of the gutters collected large volumes of runoff and it would be reasonable to assume that different hydraulic potentials within the soil, combined with the exceptionally high amount of rain, provide a possible explanation for these high quantities of flows.

Another period of high collected flows was in July 1985. However, in this case it is striking that gutter C1 collected a considerable runoff amount during the period (between 23 and 30/7/85) when 128mm of rain was measured, whereas gutters A1 and B1 collected comparatively low amounts. It is difficult to give an adequate explanation for this, however, it is possible that local differences in water potentials (i.e. at plot C)may have led to the high observed lateral flow in gutter C1.

5.4 Variation between plots

Although the temporal pattern of the runoff per plot is similar over time (Fig 5.2), the total amounts collected at the end of the two field seasons (per plot and per gutter) varied as shown in Table 5.5.

Table 5.5

Total runoff (millimetres) per gutter and per plot over two experimental field seasons

gutter	plot A	plot B	plot C
1	16	67	148
2	66	20	6
3	8	2	1
total runoff	90	89	155

As has already been pointed out, gutter A2 not only collected flows quite frequently but also accumulated a large amount.

PLot B accumulated a significant quantity in gutter B2, whereas plot C accumulated practically nothing in gutter C2. Very little reached the third gutter (A3, B3 and C3) in any of the plots. Again, making allowances for possible overestimation of the flow quantities in gutter A2, it is possible to see that the larger water quantities in all three plots occurred in the topmost gutters.

5.4.1 Reproduceability of the results and estimates of variance

In this work, one of the major objectives is to consider whether or not the plots can give an accurate picture of what is happening in terms of flow distribution in time and amount over the study site.

In order to assess this problem, two-way analysis of variance were performed for the number of times runoff occurred and for the total outflow from each plot for the two field seasons. However, prior to this, a non-parametric test (Mann-Whitney) was used as the data had a non-normal distribution. Results of both parametric and non-parametric tests were identical, implying that the results of the analysis of variance would not be misleading.

Details of the analysis of variance are given in Tables 5.6 and 5.7.

Table 5.6

Variance estimate for the number of times runoff occurred in the three plots
(F ratio at 1%)

source	DF	SS	MS
plots	2	4.22	2.11
gutters	2	678.22	339.11
residual	4	94.45	23.61
total	8	776.45	

F gutters = 14.3

F plots = 0.089

Table 5.7

Variance estimate of the runoff amounts measured on the three plots
(F ratio at 1%)

source	DF	SS	MS
plots	2	953.56	476.78
gutters	2	8253.56	4126.78
residual	4	9906.77	2476.69
total	8	19113.89	

F gutters = 1.66

F plots = 0.192

From the results of these analyses (Table 5.6 and 5.7) it is apparent that there is no significant difference between the three plots in terms of predicting total runoff events and amounts over the two field seasons. Despite this, there is a very large residual shown in Table 5.7, and this is probably due to runoff variation in time and field variability which however, is not sufficient to affect the total amounts observed over the two field seasons.

Further analysis was carried out by using a simple MINITAB (Ryan, Joiner and Ryan, 1976) regression model to regress runoff as a function of rainfall, considering only rainfall amounts greater than 5mm. Results of this statistical analysis are summarized below:

plot A runoff = - 1.21 + 0.111 rain r^2 =30.3% T=4.84

plot B runoff = -0.106 + 0.0665 rain r^2 =22.2% T=3.93

plot C runoff = -1.32 + 0.162 rain r^2 = 52.1% T=7.67

(n=56 all T ratios significant at 95%)

The linear regression models are significant. From this analysis it is apparent that this single regression model may be used as a first step in explaining the runoff events measured by the plots. However, there is still a large amount of variation unaccounted for. As the rainfall input was the same for all replicates, one would expect the responses to have been similar. The various regression coefficients for each plot indicate how the static controls vary from plot to plot.

Examining the coefficients of determination (r^2), it is clear that this model has a higher level of unexplained variation for plots A and B than for C. However, considering that it is to be expected that runoff is subjected to the influence of anumber of variables (e.g. methods of measurements, soil water potentials within the profile) then these results, using only one variable as a predictor, are encouraging and are of a similar order of magnitude to those reported by Anderson et al. (1984) for a similar experiment.

Following this analysis, the next step was to consider the residuals from the regression to see if any particular clusters occur relating to other controlling variables (Fig.5.4).

This figure shows that the variations occurred during the first part of the experiment, especially during the dry period, indicating that other factors apart from rainfall, can have considerable influence on the runoff from the plots. The positive residuals in the first part of the experiment also indicated that runoff was produced when rainfall was low. Later in this chapter, a comparison of the runoff amounts produced in the two periods (dry and wet) will be made.

From week 25 to the end of the experiment, although rainfall quantities were larger, runoff decreased as shown by the negative residuals. Further, the variation was less than in the dry period. An attempt to increase the level of explanation of the single variable regression model, was made by including a soil water content term. Results of this multiple regression, however, were not successful, i.e. the inclusion of soil water content values did not contribute an increased level of explanation. This means that further investigation will be necessary in order to identify other significant variables (e.g. soil permeability, soil water potential in the actual plots)

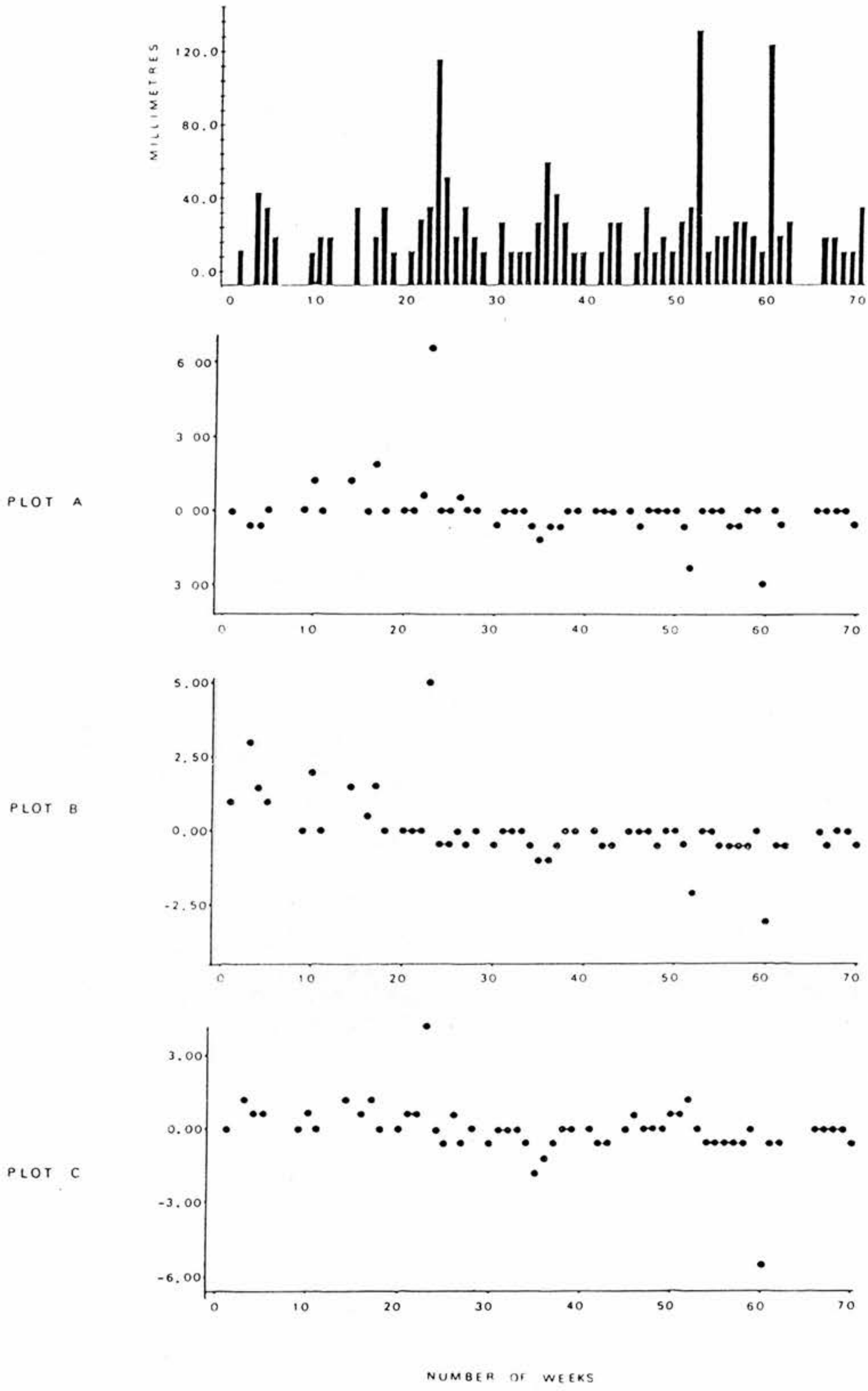


Fig. 5.4 Rainfall and scatter plot of residual terms from regressions

for such predictions to be more accurate.

As the results of the analysis of variance showed that there was no significant difference between the number of times that runoff occurred or between the total amounts measured in the plots, it was decided to use an average figure to represent the flows of the plots. This was adopted for the entire period of observation and on a week by week basis.

When considering the soil water balance on a week by week basis later in this chapter, the variation of the runoff amounts is shown as the standard deviation in the water balance tables. These error figures permit an imediate evaluation of the magnitude of the variation between plots and comparisons between results obtained in different periods i.e. dry and/or wet.

For the entire period of observation, the total runoff overthe sample was calculated using the quantity $n\bar{x}$ (n is the sample size) with a standard error given by $n\sigma/\sqrt{n}$ (where σ is the sample standard deviation) (Snedcor and Cochran, 1980). The results obtained were:

total runoff = 111.4mm

standard error = ±34.0mm

To judge the importance of the above result, it is necessary to consider: (1) the natural variation of the runoff processes over a hillslope, (2) the absence of a reference value for the error involved in such measurements, obtained for similar soil types and in similar climatic regions.

Considering the points above, the fact that it is possible to estimate runoff to within ±30%, is important as it provides a reference value for expected errors in runoff estimates from hillslopes of small catchments with similar soil types and climate. This should mean that comparable experiments can be planned knowing in advance, the likely magnitude of the error of their results.

Knowledge that plot results may have an error Of ±30% imposes a need for using replicates in such type of work. An example which shows the magnitude of the variation in plot results, and can be used to support the need for replicates in this type of work, is given by Hjelmfelt and Burwell (1984), who studied the spatial variability of runoff in 40 agricultural plots (each of 27.5m X 3.2m) in claypan soils. Variations ranging from ±1% to ±109% were found for various runoff quantities. As an example, for average runoff of 12.5mm, it was found that coefficients of variation ranged from ±1% to ±26%.

Although the transferability of these results to the soil type and climate of the current research project is not so obvious, this example supports the need for using plot replicates, implying that research projects which used only one plot to measure flows over a hillslope may have questionable results.

5.5 Soil-water balance

This section presents the results of the various hydrometeorological processes measured during the project in the form of a soil water balance.

The water balance, given earlier in equation (2.1), can also be expressed in the form

$$\text{Deep} = P - R - AE \pm \Delta Sw \qquad (5.1)$$

where,

Deep = deep drainage

P = precipitation

R = runoff (total of 3 gutters)

AE = actual evapotranspiration

ΔSw = change in soil water content, to a depth of 60cm.

(all components in millimetres)

As the terms P, R and ΔSw were measured at the study site and actual evapotranspiration data was obtained from MORECS weekly summary sheets, the term Deep could be calculated. The term deep drainage, in this thesis, is used to signify all drainage passing vertically through the soil profile, below 60cm (ie the lowest point of measurement).

Soil water balance studies, as shown in Chapter Two, provide a valuable format for the understanding of dynamic processes of water movement and storage in the soil.

The main objective in determining the soil water balance was to demonstrate whether the experiment was giving plausible results over replicated plots. In order to achieve this objective, the water balance was used to consider the following characteristics:

1. The seasonal pattern of moisture supply at the study site, considering the climatic influences involved
2. Occurrence of a soil moisture deficit
3. The time when runoff and/or deep drainage should be expected as derived from the moisture excess in the soil
4. The amount of deep drainage in the study site.

5.5.1 Seasonal pattern of moisture supply at the study site

In this section a broad view of the soil water balance is presented on a monthly basis for the whole period of observation. This broad picture highlights the dry and wet periods, evaporative demand and the occasions when runoff and deep drainage should be expected. Explanations about the occurrence of runoff and deep drainage were based on the matric potential differences within the soil profile. Lateral runoff from the soil occurs while hydraulic potentials differ within the soil profile. However, when the soil becomes completely wet at high and uniform potentials, lateral runoff decreases or ceases and deep drainage prevails. In other words, when the soil was at moisture deficit (i.e. below field capacity) hydraulic potential differences prevailed in the profile encouraging lateral runoff. As the soil moisture deficit was replenished by rainfall, the soil profile reached its field capacity and hydraulic potentials were uniform, thus any excess amount of rainfall was hydrologically effective in terms of drainage from the bottom of the profile.

Examination of Fig. 5.5 for the whole set of observations, allows the definition of the major dry and wet periods, by defining a dry period to be when the soil is drier than field capacity and wet periods when the soil is at or above field capacity. A rapid glance at the pattern of results (Fig. 5.5) shows that the dry periods were very different for the two field seasons. In both seasons, a soil moisture deficit had developed by mid-May, i.e. the soil was drier than field capacity. However, in 1984 the dry period was longer and more severe (as shown by the low matric potentials in Fig. 5.6) extending until mid October, whereas in 1985 the soil moisture deficit had been removed by mid-June, and the soil remained wet until the end of the season (Figs. 5.5 and 5.6).

The monthly soil water balance for the study site for the eighteen months of the study is shown in Table 5.8 and illustrates the distinction between the seasons:

Table 5.8

Monthly water balance for the study site 1984/85 (all figures in millimetres)

	1984								1985									
	M	J	J	A	S	O	N	D	M	A	M	J	J	A	S	O	N	D
P	47	71	28	21	91	79	209	58	39	130	57	50	207	92	173	47	46	135
PE	65	69	100	60	47	37	17	15	24	54	53	69	79	65	40	32	15	12
PE-P	18	2	-72	-39	44	42	192	43	15	76	4	-19	130	27	133	15	31	23
SMD	18	16	88	127	83	41						19						
SURPLUS							151	43	15	76	4		111	27	133	15	31	

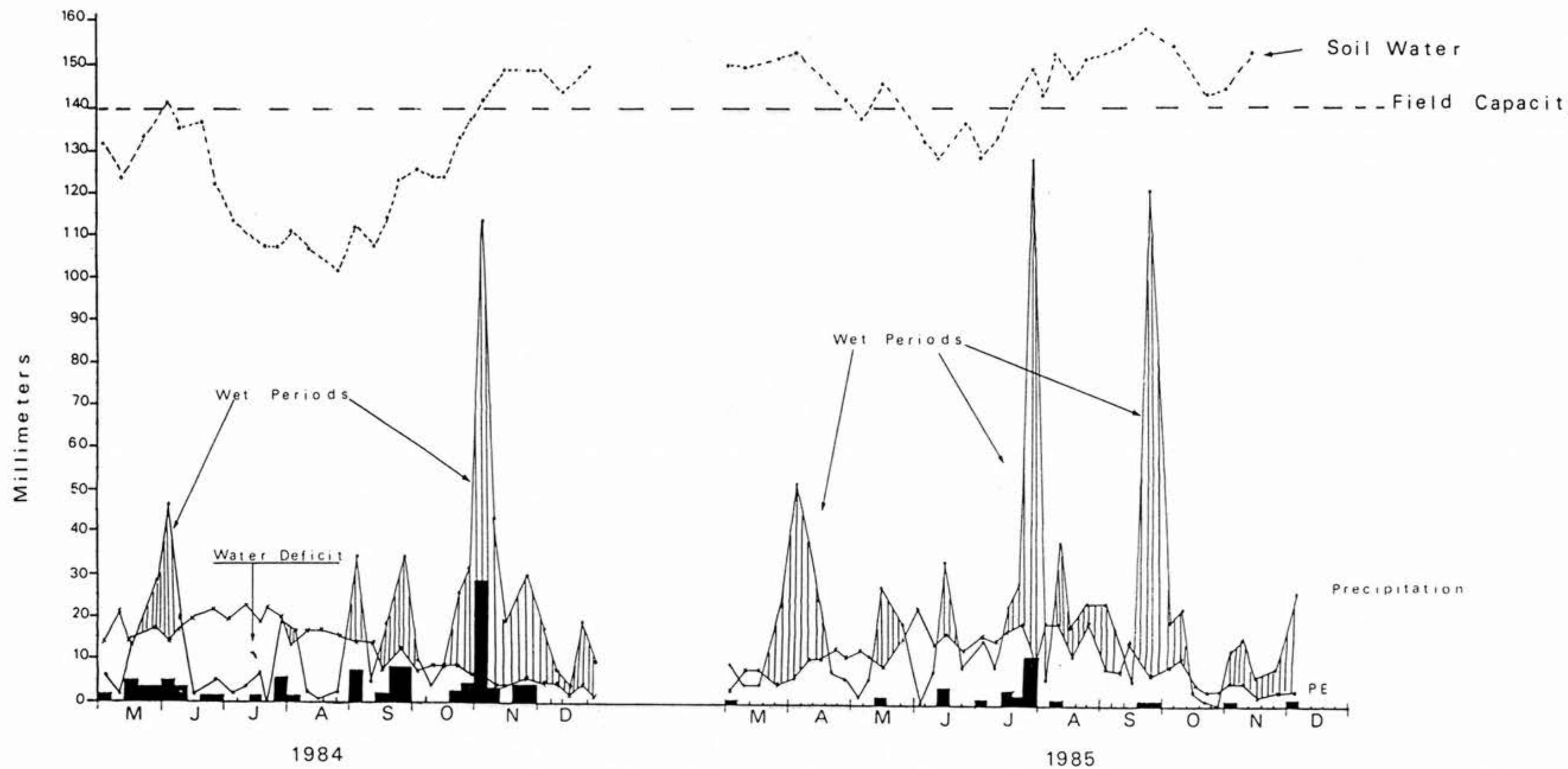


Fig. 5.5 Precipitation, actual evapotranspiration, total water content and average runoff (shown as bars)

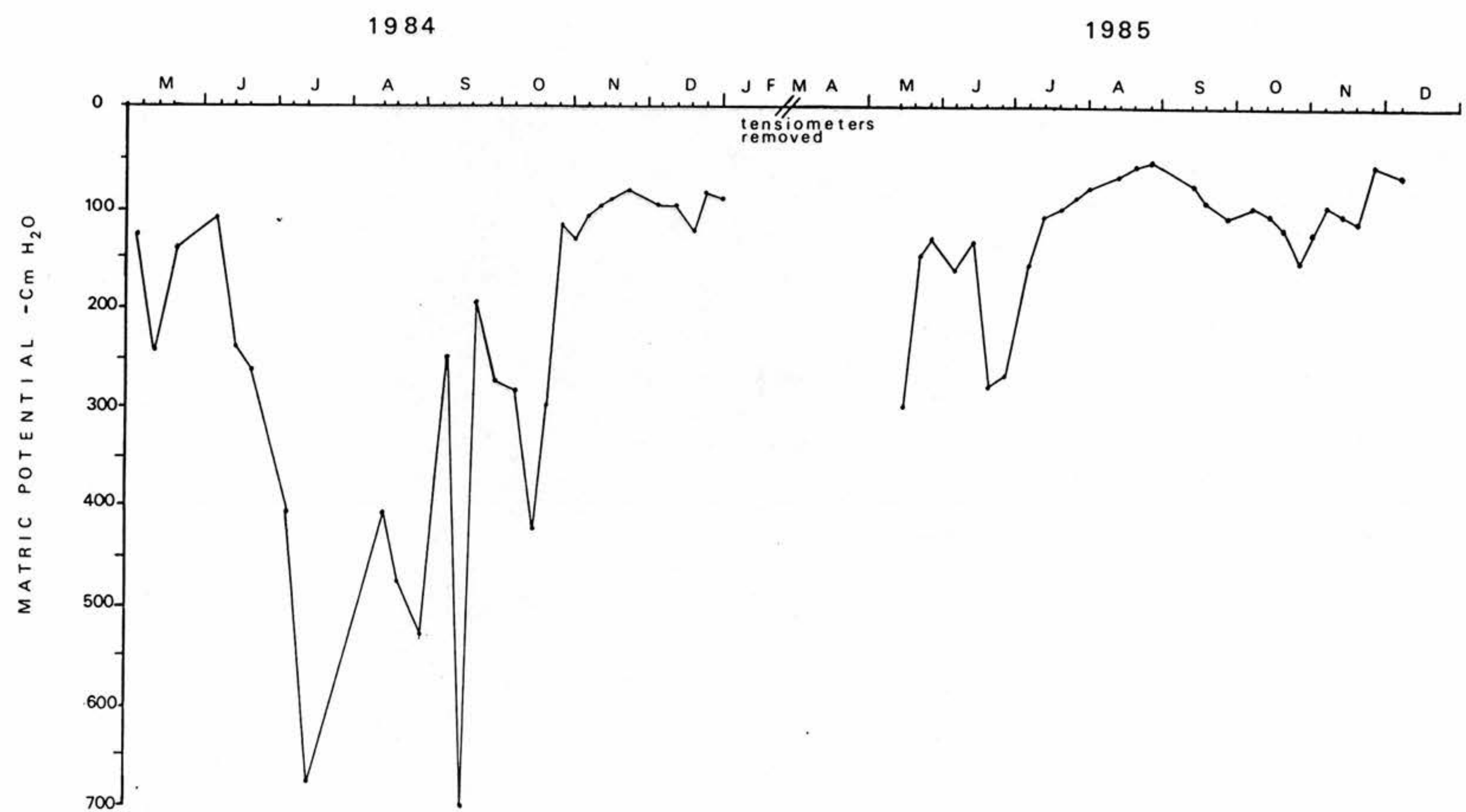


Fig. 5.6 Measured matric potential as a function of time near the top of root zone (10cm) in the study site

Row 1 is the monthly precipitation; row 2 is the potential evapotranspiration obtained from MORECS, row 3 shows the soil mosture deficit, with positive values showing the net input of water entering the soil; rows 4 and 5 are respectively, cumulative soil moisture deficit and net monthly surplus of water entering the soil.

5.5.2 Analysis of the weekly soil water balance

This section gives a more detailed account of how the plot runoff characteristics were affected by the soil moisture fluctuations. The analysis was carried out weekly, describing the rainfall amounts, moisture potentials and soil water content in order to explain runoff and deep drainage events. During the analysis, attention was paid to the distinction of shorter term 'wet' periods (shown in Fig. 5.5 by the shaded areas when the weekly input of precipitation was in excess of the evaporative demand). Although these 'wet' periods may only reduce the cumulative soil moisture deficit, it is during these periods, when there is excess water, that flow processes may occur (runoff and/or deep drainage).

Occasionally, periods of two weeks were added together, especially in the prolonged dry and wet spells as little variation was likely to occur in the soil water content. During these periods only fortnightly neutron probe observations were made. For the purpose of the analysis, based on the results of the particle size analysis (Chapter Three) the soil was classified as sandy-loam, with a total water content at field capacity of 140mm, as determined from the moisture release experiment.

Before commencing the analysis of the weekly water balance however, it is necessary to examine the neutron probe and tensiometer data. The neutron probe data must be examined to consider the similarities and contrasts between the treatment rows which would permit the selection of a representative sample for the determination of the average soil water content. In the case of tensiometer data the objective was to consider the error in the measurements and, pehaps more importantly, to evaluate the effects of an artificially exposed face on the measurements.

Neutron Probe data

As mentioned in Chapter Four, four rows of three neutron probe access tubes were installed as a part of the experiment. Examining Fig. 5.7 (rainfall) and 5.8 (cumulative change in water content), it is apparent that rows 1, 2 and 3 are very similar, whilst row 4 appears to have a different temporal pattern showing lower total water loss from this part of the profile. It is also interesting to notice that, by the end of the dry period, the four rows were ranked according to their position over the slope, with row 1 drier than rows 2, 3 and 4, perhaps indicating that the water was moving laterally, parallel to the surface towards row 4 where the topsoil layer was shallower at the break of the slope. This movement of water towards

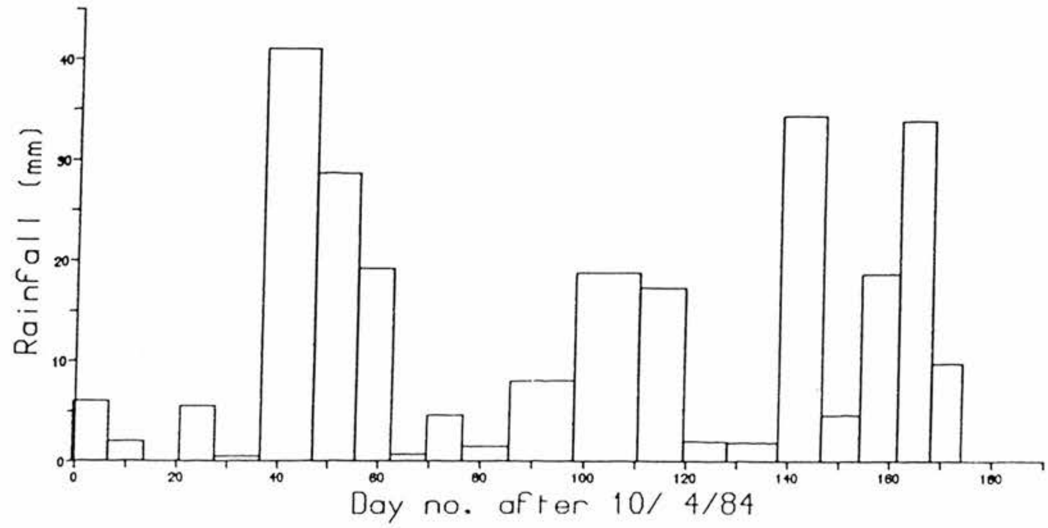


Fig. 5.7 Rainfall from 10/4/84 to 2/10/84
(day no. 0 to 175)

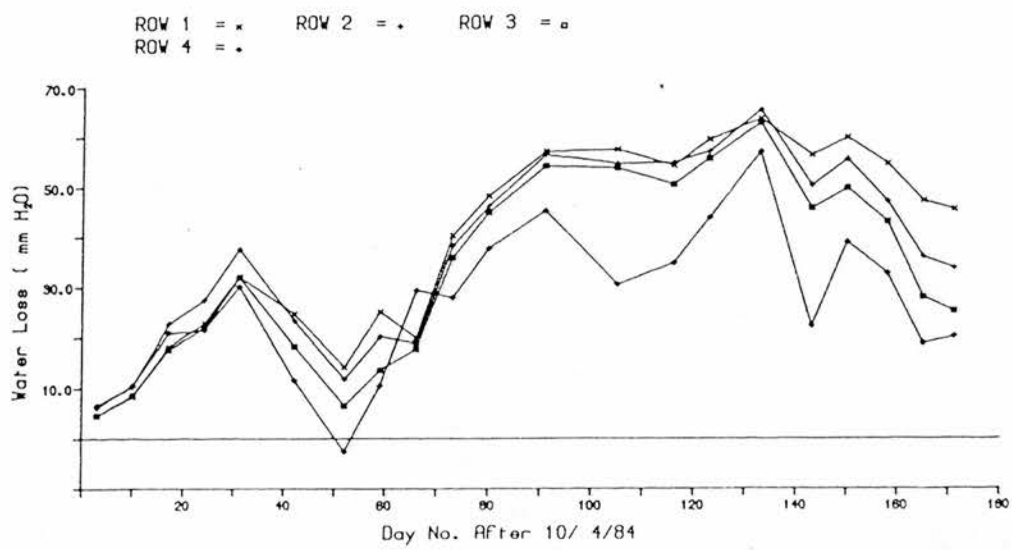


Fig. 5.8 Cumulative change in water content
(day no.0 to 175)

row 4 during the dry period, confirms that whilst the soil was relatively dry lateral water movement occurs parallel to the surface, as already shown by Brady (op.cit), Zaslavski and Sinai (op.cit), and Hewlett and Troendle (op.cit) obeying a preferential lateral potential gradient.

Similarly, when comparing Fig.5.9 to 5.12, it is also apparent that row 4 had a different behaviour from the other three rows. In all circumstances significant changes in water content occurred to a depth of 40cm, (revealing a depth zone in the soil profile which contributes more actively to evaporation), with only small changes occurring at 50cm, and no significant changes at 60cm. However, for all depths within the profile for row 4, any decrease in the soil moisture content is marked by a subsequent increase, and this recharge is not so evident for the other rows. This effect is most noticeable on day 150 when the perturbation caused by the rainfall of the previous week extends down through the entire soil profile, whereas for rows 1 to 3 a significant increase is only noticed at 5cm depth.

It is not remarkable that row 4 behaves differently in view of its position in the slope relative to the other three rows. At the beginning of the study it had been intended to have a second experimental site at the base of the hillslope and thus row 4 was sited just below the break of the slope down from the present site. It was expected that a row of access tubes located in this position would be able to reveal when lateral flow of water down the slope increased. Thus, it will be of interest later to compare any pertubations detected by row 4 with the outflow results from the main plots upslope.

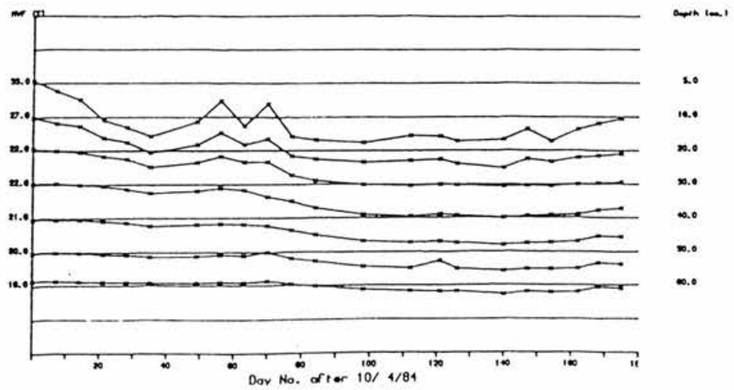


Fig. 5.9 Soil moisture content (%) at each depth - Row 1

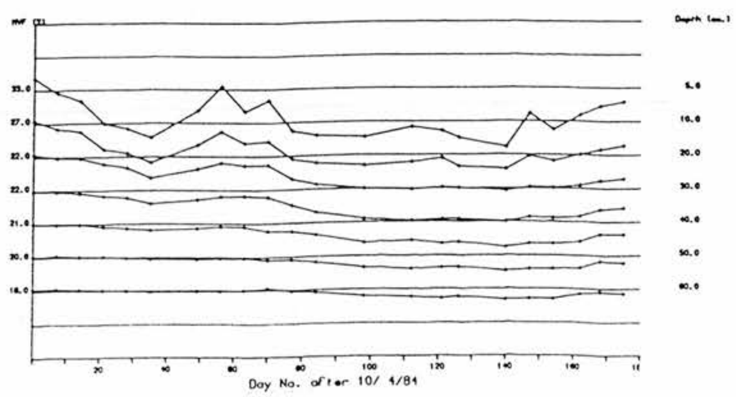


Fig. 5.10 Soil moisture content (%) at each depth - Row 2

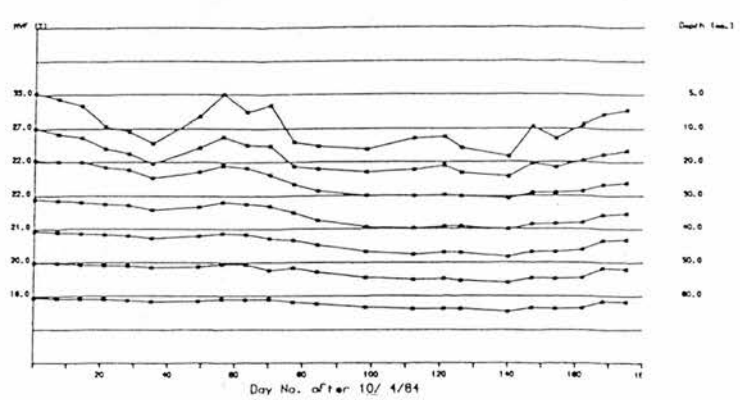
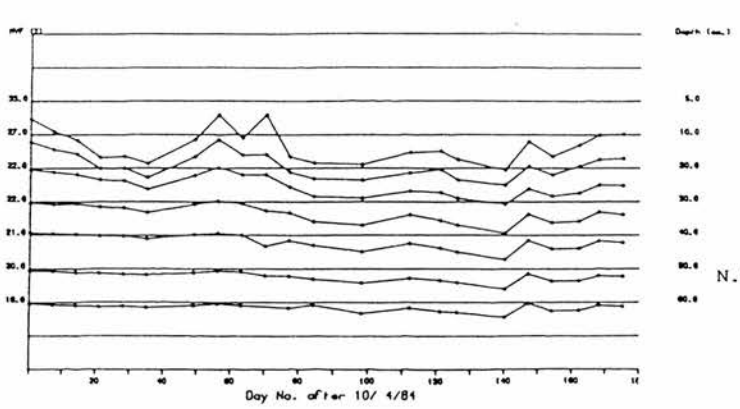


Fig. 5.11 Soil moisture content (%) at each depth - Row 3



N.B. MVF values on vertical axis are arbitrary origins for each depth. However, the scale for the vertical axis is 10 MVF% per cm.

Fig. 5.12 Soil moisture content (%) at each depth - Row 4

The location of rows 1, 2 and 3, upslope on a more level area, as opposed to row 4, contributed to the uniformity of the results as demonstrated above. In view of this, they were selected as being a representative sample for the determining of the average water content and the average change of water content in the dry period.

For the wet period (here shown from the beginning of October, excluding January and February, to the end of March 1985 for ease of presentation), the four rows exhibited basically the same temporal pattern. Row 1 was drier than rows 2, 3 and 4 at the beginning of the period, but as the soil became wetter there was no significant differences between the rows, as shown in Fig. 5.13 and 5.14. The individual rows are shown in Fig. 5.15 to 5.18.

Similarly, for the rest of the experiment (i.e. from end of March to beginning of December 1985) as a result of a very wet soil, there is no apparent significant difference between the rows, as can be seen in Fig. 5.19 and 5.20. Fig. 5.21 to 5.24 show the behaviour of the individual rows during the period.

This similarity between the rows, starting at the beginning of the wet period of 1984, which prevailed up to the end of the second field season meant that, in effect, all four rows could have been averaged. However, to maintain consistency with the long period (above) only rows 1-3 were averaged to give a representative result for the mean water content at the study site.

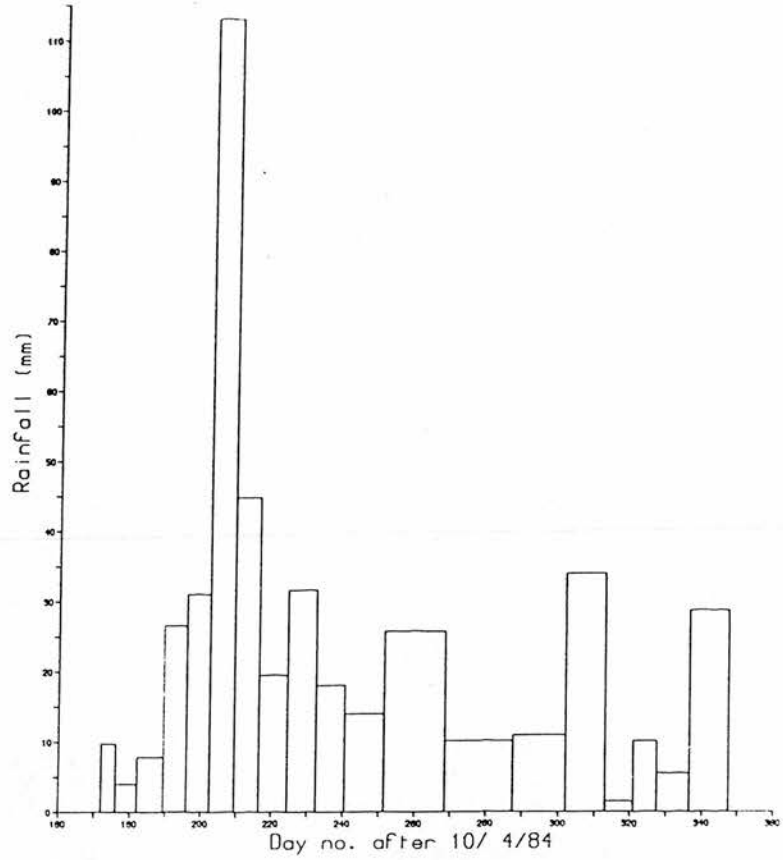


Fig. 5.13 Rainfall from 9/10/84 to 26/3/85
(day no. 182 to 349)

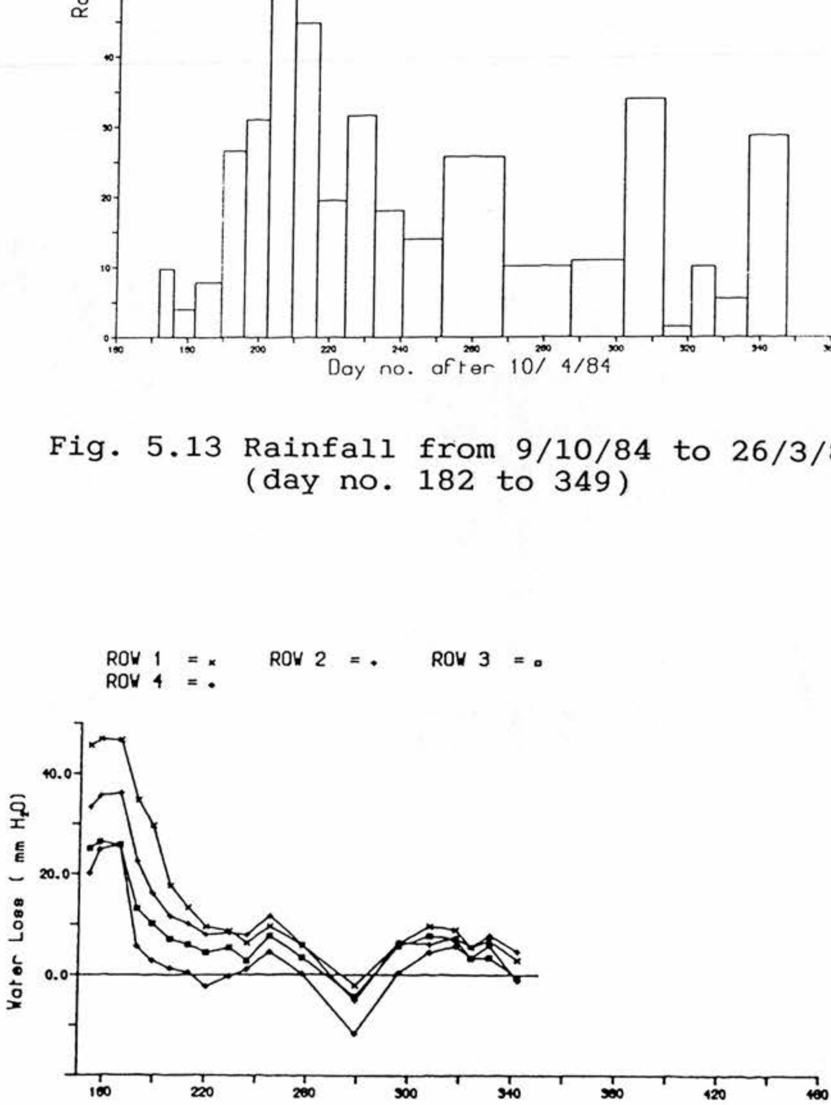


Fig. 5.14 Cumulative change in water content
(day no. 182 to 349)

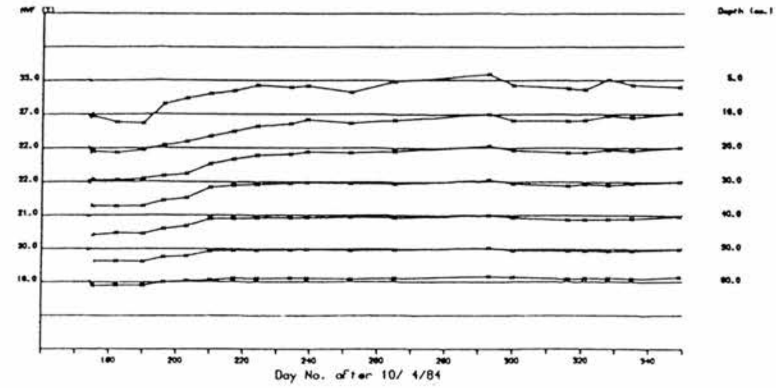


Fig. 5.15 Soil moisture content (%) at each depth - Row 1

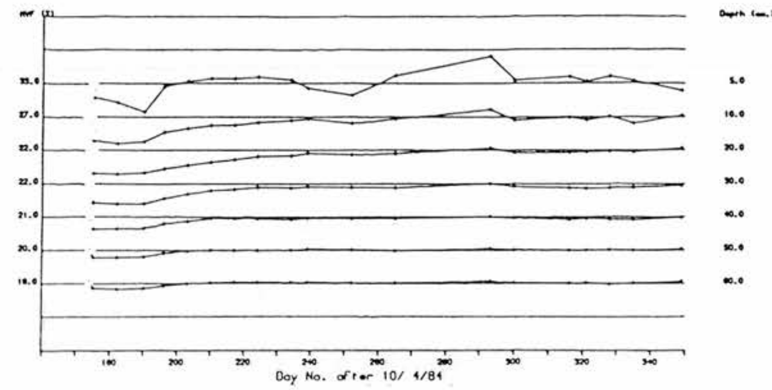


Fig. 5.16 Soil moisture content (%) at each depth - Row 2

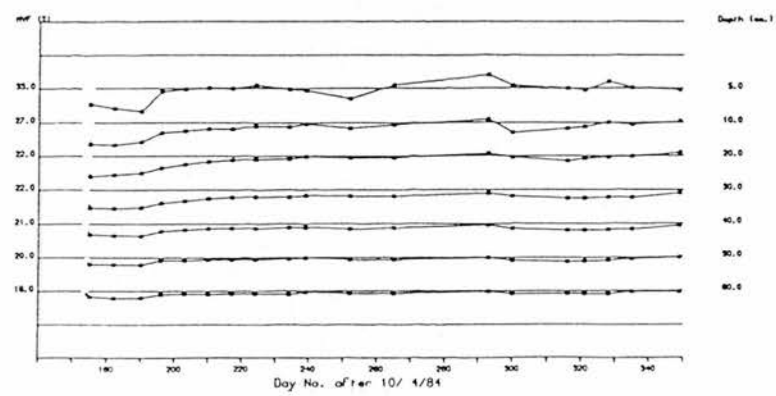
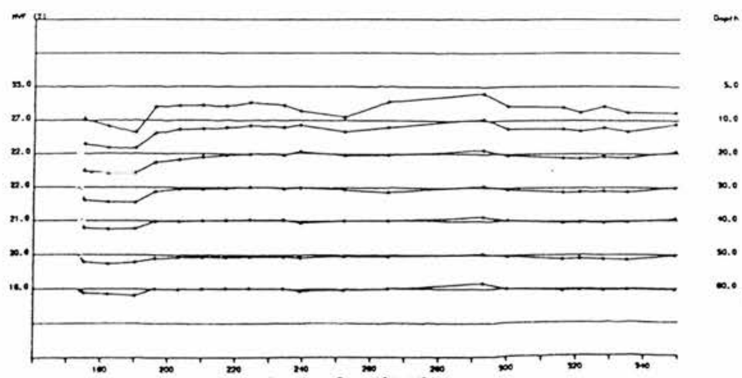


Fig. 5.17 Soil moisture content (%) at each depth - Row 3



N.B. MVF values on vertical axis are arbitrary origins for each depth. However, the scale for the vertical axis is 10 MVF% per cm.

Fig. 5.18 Soil moisture content (%) at each depth - Row 4

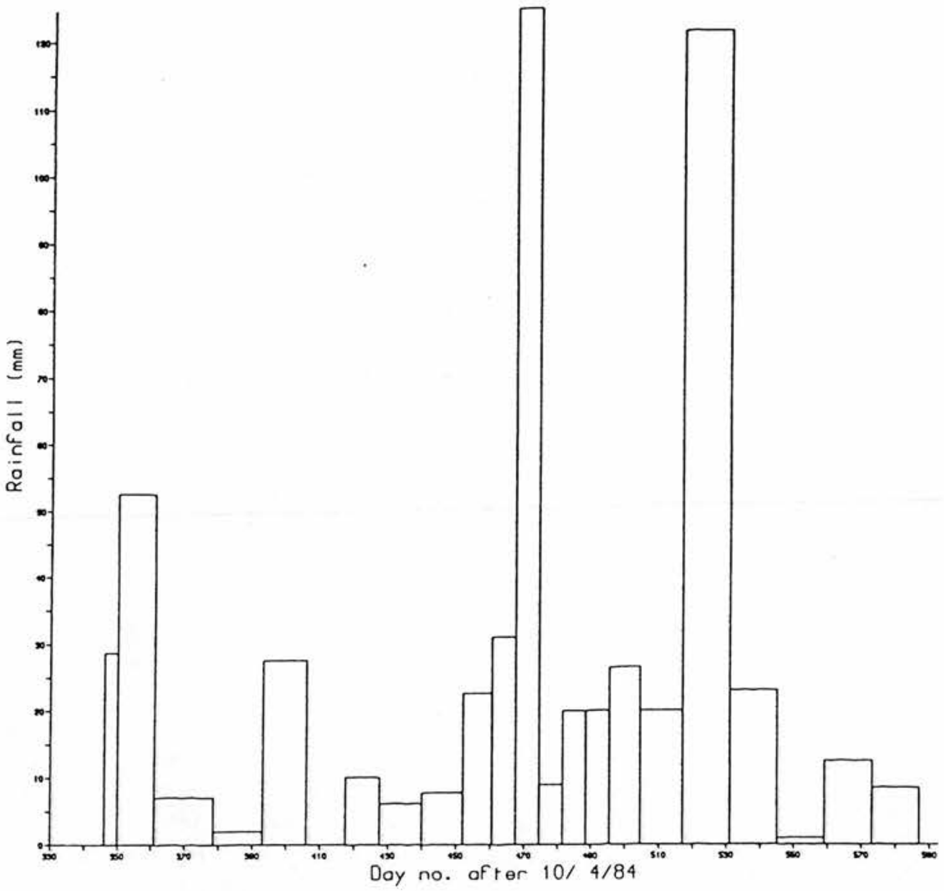


Fig. 5.19 Rainfall from 2/4/85 to 19/11/85
(day no. 356 to 580)

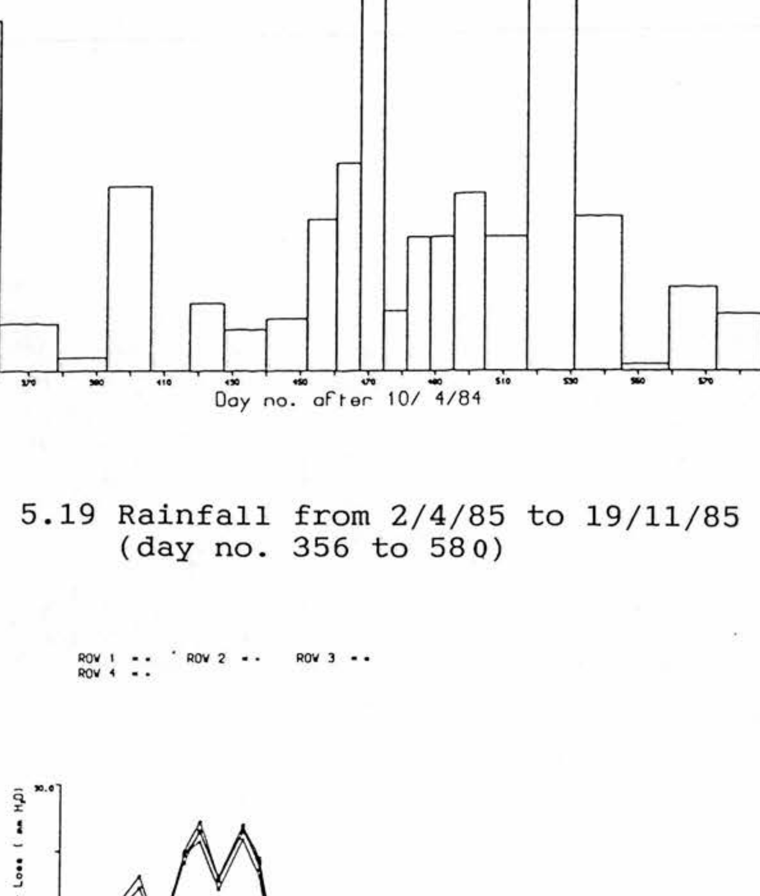


Fig. 5.20 Cumulative change in water content
(day no. 356 to 580)

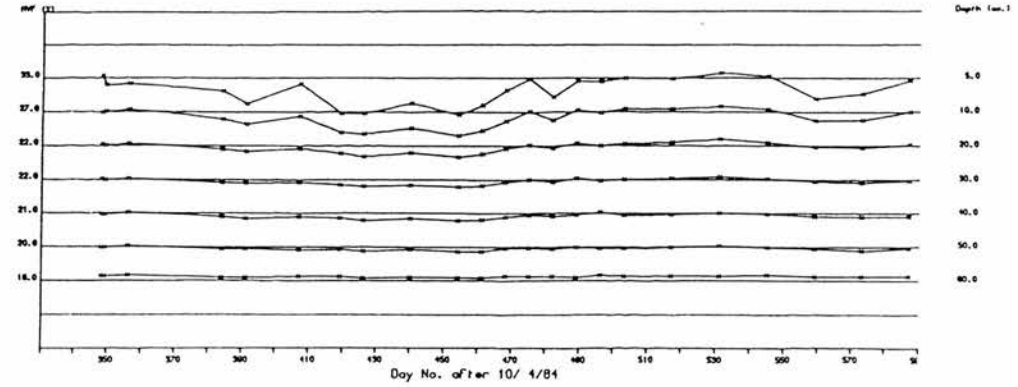


Fig. 5.21 Soil moisture content (%) at each depth - Row 1

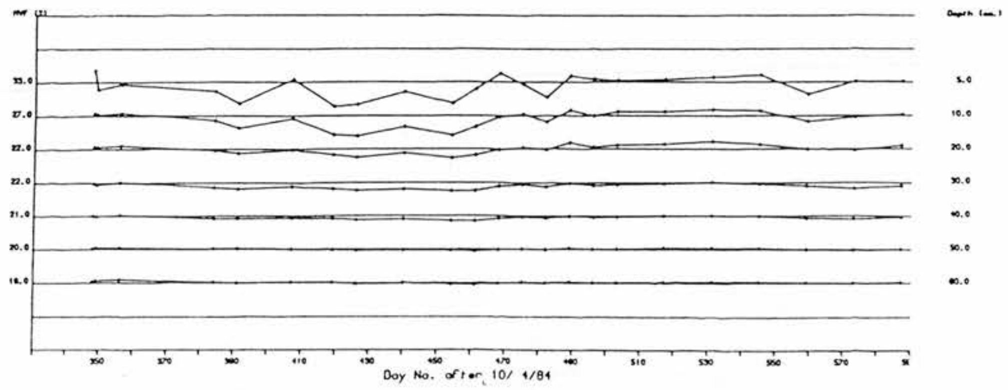


Fig. 5.22 Soil moisture content (%) at each depth - Row 2

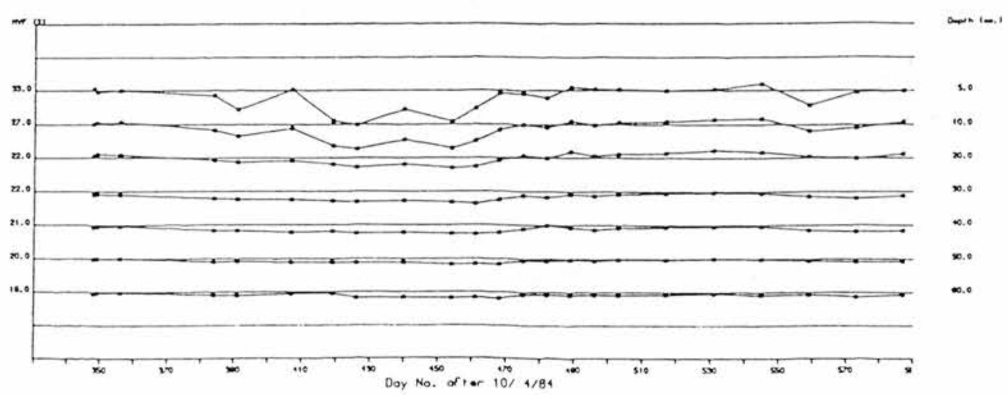


Fig. 5.23 Soil moisture content (%) at each depth - Row 3

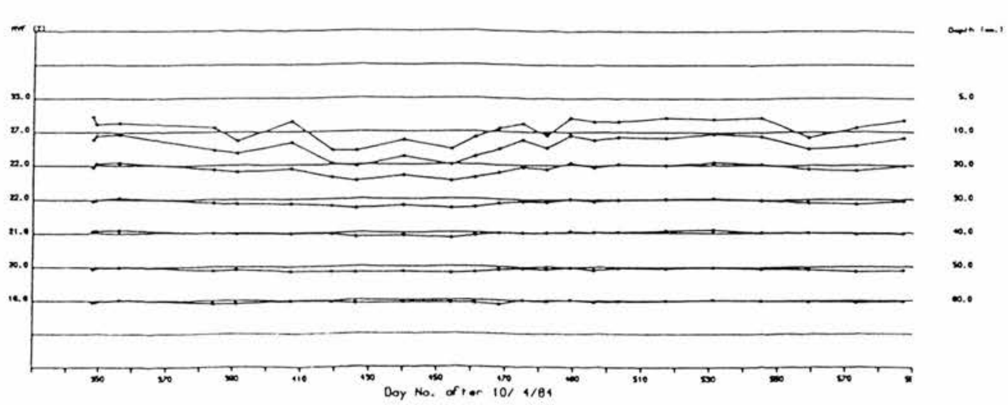


Fig. 5.24 Soil moisture content (%) at each depth - Row 4

N.B. MVF values on vertical axis are arbitrary origins for each depth. However, the scale for the vertical axis is 10 MVF% per cm.

The similarity between rows during the wet period, either in 1984 or 1985, shows that as the soil gets wet vertical movement of the water down the soil profile is more significant than lateral movement, as demonstrated earlier in Brady's experiment. More detailed evidence of this behaviour of the soil water during the wet period will be presented later in this chapter.

Tensiometer data

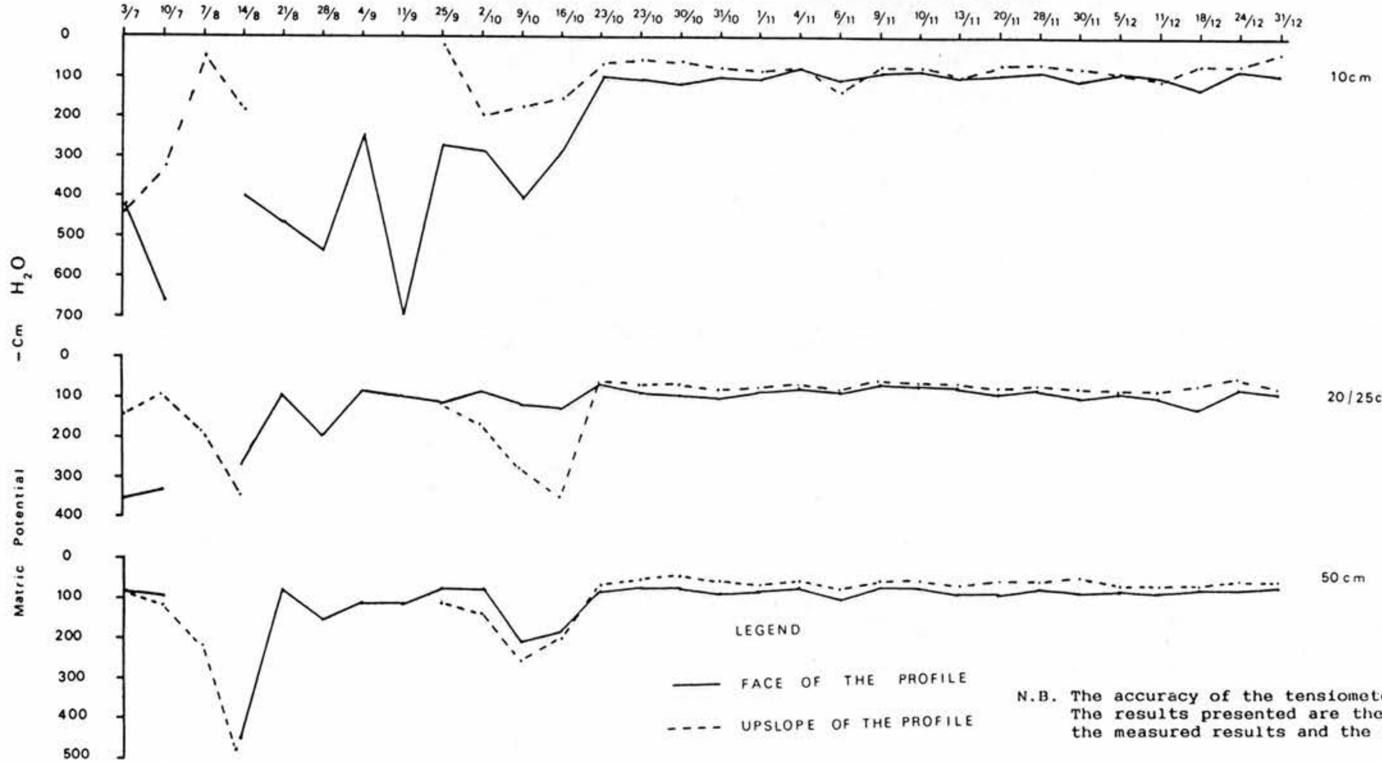
As pointed out earlier, flows of water were collected in gutters installed in an exposed vertical face of the soil at different horizons in three plots. Tensiometers were needed to give information on the direction of the water movement within the soil profile and were installed in the free face of the trench next to the bounded plots and also 2.5m upslope from the plots. The data of the tensiometers also helped to determine when soil was under moisture deficit or at field capacity, thus allowing inferences about the occurrence of lateral flows.

The presence of an exposed artificial free face was bound to cause disturbances, influencing both water flows and matric potentials. Low flow quantities were expected to occur due to the break in the hydraulic continuity of the soil, possibly resulting in an increase in the soil water potentials at the free face. However, in opposition to this, an exposed face will dry out faster which may result in lower matric potentials. Therefore, it was important to assess the net effect of these two contradictory factors.

In this section data from the tensiometers located in the free face of the pit and upslope of the plots is presented in order to assess any such effects. The influence of the artificial plot boundaries on the flow of water will not be considered here, because tensiometers were not installed in the actual face of the plots.

The data set was divided to represent the dry and wet periods of both years. It was not possible to compare tensiometer data in May and June 1984, as only a single nest of tensiometers had been installed upslope at this stage. Later in the dry period (17th July - 31st July), the matric potential on the face and upslope of the pit fell below -850cm and thus tensiometer data could not be obtained. The face tensiometers failed again on 7th of August. Later, from 21st August to 11th September, the upslope tensiometers failed, despite attempts to recharge them. It is also necessary to repeat that the free face tensiometers were installed at 25cm depth compared with 20cm in the upslope sites.

Making these allowances and analysing Fig. 5.25 for the matric potentials measured from 3/7 to 31/12/84, it is possible to see that throughout most of the dry period, although the upslope tensiometers have a slightly higher potential, there was no significant difference between both sets of tensiometers at all depths, except on 10/7 and 14/8 at 10cm depth. At the beginning of the wet period (mid October) there are two possible significant differences,



N.B. The accuracy of the tensiometer is given below.
The results presented are the average standard deviation of the measured results and the range of the standard deviation

Tensiometers on the face of the profile

Depth (cm)	Std dev. (-cm H_2O)	Range
10	53.5	(44.4 - 133.0)
25	42.9	(32.0 - 126.0)
50	45.1	(35.0 - 108.0)

Tensiometers upslope of the profile

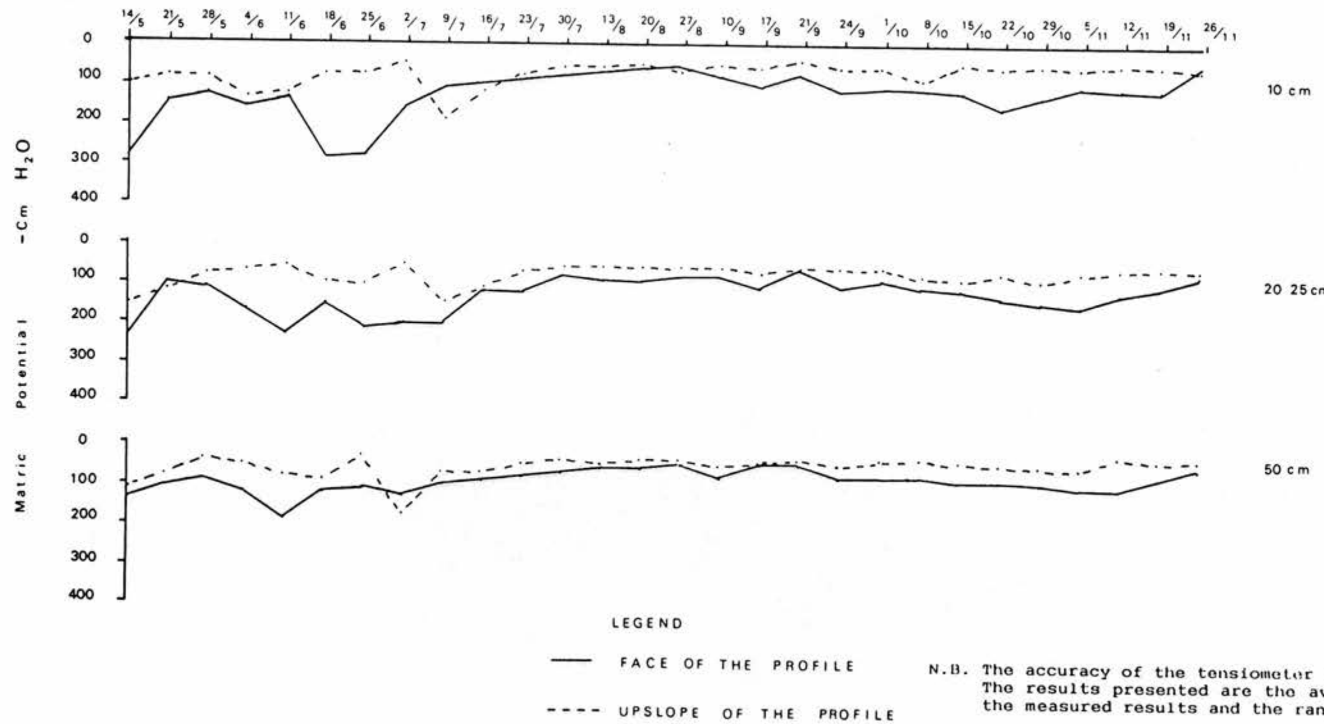
Depth (cm)	Std dev. (-cm H_2O)	Range
10	52.6	(7.0 - 173.0)
20	36.2	(17.0 - 137.0)
50	58.2	(16.0 - 180.0)

Fig. 5.25 Comparison between matric potentials measured from 3/7 to 31/12/84

9/10 (at 10cm) and 16/10 (at 20/25cm), but as the soil returns to field capacity quite similar matric potentials are measured in both sets of tensiometers at all depths.

In the second field season, Fig. 5.26, it is possible to see that the probable significant differences between the sets of tensiometers occurred on 18th and 25th June (at 10cm), during the short period when a soil moisture deficit existed during this season (1985). However, no significant differences between the both sets of tensiometers, at all depths, is noticeable from July onwards. This behaviour of the tensiometers may be due to the fact that the soil returned to field capacity in July (as already mentioned) and remained at field capacity until the end of the field season.

From examination of the Fig. 5.25 and 5.26, it is possible to see that any differences between tensiometers were only significant in the dry period, especially in 1984, when tensiometers both in the face and upslope were subjected to higher variations. However, as the soil gained water and returned to field capacity, there was a better agreement between both sets of tensiometers. This agreement is most apparent in the wet period of 1984 and throughout most of 1985. It is also noticeable that by October and November 1985, as precipitation fell below average (Table 5.2), the potentials decreased in the face of the profile, but, as during this period the evaporative demand was low, this 'dry period' was not sufficient to lower the



N.B. The accuracy of the tensiometer is given below.
The results presented are the average standard deviation of the measured results and the range of the standard deviation

Tensiometers on the face of the profile

Depth (cm)	Std dev. ($-cm\ H_2O$)	Range
10	43.8	(7.7 - 99.6)
25	26.0	(4.2 - 67.0)
50	25.2	(2.6 - 72.0)

Tensiometers upslope of the profile

Depth (cm)	Std dev. ($-cm\ H_2O$)	Range
10	33.5	(0.4 - 87.2)
20	33.5	(1.6 - 109.2)
50	23.3	(2.4 - 42.5)

Fig. 5.26 Comparison between matric potentials measuredfrom14/5 to 26/11/85

potentials in the soil upslope of the pit. This implied that at both sites the soil remained at, or very near, field capacity as there were no significant differences between the both sets of tensiometers. As a consequence of the uniformly wet soil (especially in 1985) the error in the measurements decreased as can be seen in the Fig. 5.25 and 5.26.

From the matric potential data presented here, it does not appear that the construction of the pit in the middle of the slope, caused serious disturbances to the distribution of the potentials in the soil profile. It is however worth mentioning that during a dry period, as an artificial free face may dry out faster than an undisturbed soil, the water potentials are lowered which means that water is at sub-atmospheric pressure, unable to leave the pore space of the soil. The significance of this is that an artificial free face may lead to a lower production of flows under dry conditions thus underestimating the amount of lateral runoff from the soil that may occur in an undisturbed soil.

Finally, as the differences in matric potential were confined to a few occasions in the dry period, it is not possible to confirm that the construction of an artificial free face in the middle of a hillslope does affect the soil hydraulic potential network. This is also supported by the fact that the unconfined plot did not produce flows of water on any occasion, including those occasions when the other plots failed to generate flows. In other words it had the same temporal pattern as those of the other three plots (see Appendix C). Therefore, from this observation it appears that the influence of an artificial pit on the soil water regime is more likely to be significant in the foot slope areas as already pointed by Atkinson (op.cit).

Analysis of the weekly water balance: pattern of observations

The analysis of the weekly water balance will be carried out separately for the dry and wet periods over the course of two years of observation. As indicated earlier in section 5.5, the distinction between dry and wet periods is determined by considering whether the soil is below or at field capacity respectively.

Measurements of rainfall, soil moisture content and runoff started during the week ending on 8/5/84, providing the first weekly block of data. However, as the installation of the soil tensiometers was carried out gradually, complete sets of measurements were only available from 22/5/84. In the analysis, only the matric potentials measured in the free face will be used to explain the flows from the gutters, as these tensiometers were closer to the bounded plots. However, references may be made to the tensiometers installed upslope, when significant differences occurred between both sets of data in order to highlight any disturbances caused by the pit.

During the subsequent analysis the following points will be considered.

1. Lateral runoff generation.

2. Deep drainage occurrences.

Considering the first point, the lateral runoff from the plots is assumed to occur in dry soil while there is a potential gradient between the topsoil and the mineral subsoil. As the moisture increases in the top soil (potential higher than -100cm H_2O), water starts moving down, wetting the whole profile. Eventually the soil will be at uniform hydraulic potential and lateral flow will cease giving rise to vertical waterflow.

Although this assumption for explaining runoff from the plots using tensiometer data appeared adequate, it has several constraints. One of the major limitations is that the measured runoff is the total outflow collected over a period, whereas the water potential data is based on single point (both temporal and spatial) observations. This means that there is little information about actual behaviour of the potential gradients during any sampling period. An attempt to overcome this problem partially was made by considering the matric potentials both at the start and at the end of each period to assess how they may have changed.

When considering deep drainage, field capacity estimates are required and these are shown in Table 5.9.

Table 5.9

Water content (%) at field capacity
(-50cm H_2O)

soil layer (cm)	water content (%)
10 - 20	27.05
20 - 30	33.64
30 - 40	21.55
> 40	22.12

In table 5.9 the values for water content at field capacity for depthsfrom 0 to 10cm were omitted. This was because the organic matter content of the sample was too high. Drying at 105°C produces some loss of weight due to decomposing organic matter which leads to an overestimation of the water content (Gardner, 1965). In relation to the occurrence of deep drainage, it is useful to mention that it may occur when the soil is below field capacity, a phenomenon termed 'summer percolation' (Greenfields, 1981) which brings difficulty when using field capacity concept to deal with deep drainage in the dry period.

In the discussion, the water content values at field capacity obtained from the soil moisture curve will be compared with the potentials to refer to the dryness or wetness of the soil, (i.e. moisture deficit or surplus). However, the use of these values is complicated when applied to the field situation, due to hysteresis. The soil moisture characteristic curve shown in Fig. 5.27 is a desorption curve, however, if the process is reversed,

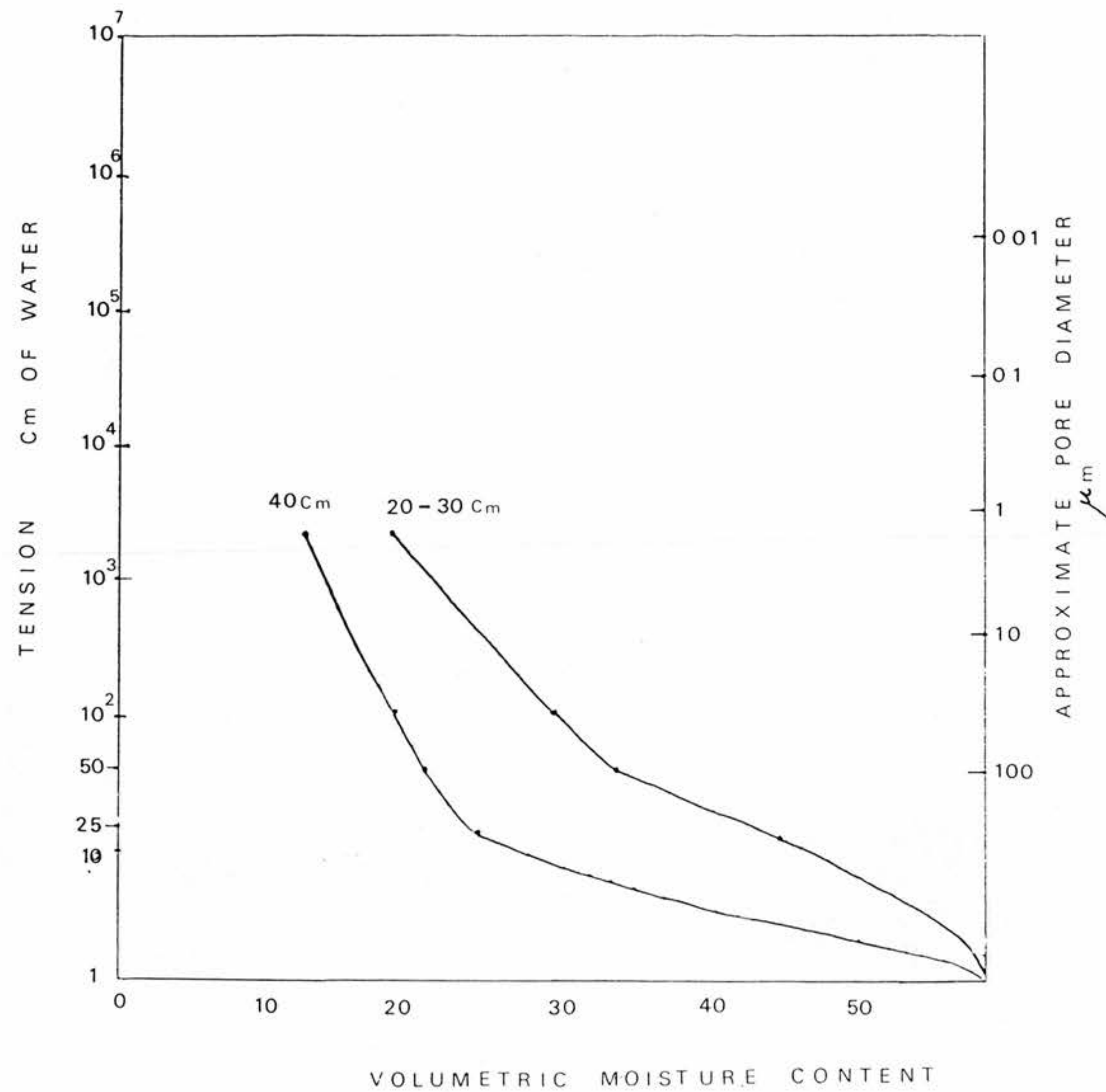


Fig. 5.27 Soil moisture characteristic curve for 20 - 30cm depth and depths equal and greater than 40cm

i.e. re-wetting (sorption) a different curve is traced, implying that a wetting soil has a lower moisture content than the drying soil at the same potential.

Fig. 5.27 which represents the moisture release characteristic curve at two depths, can also be used to estimate the distribution of pores within the soil matrix. From the shape of this curve and considering the soil textural classification, there are significant amounts of large pores which will encourage rapid drainage vertically down the profile. Finally, in order to give an idea about water losses through the profile, a value of hydraulic conductivity (for the soil at a potential of -10cm H_2O) of 35 cm/day will be used, as proposed by Brady (op.cit) for sandy-loam soils.

Results for the dry period of 1984

As already stated, the dry period of the first field season extended from May to the end of October, when the soil returned to field capacity.

Prior to considering the analysis of the weekly balance, it is of interest to examine the moisture content (MVF%) in each layer of the soil profile, the cumulative change in water content (mmH_2O) for the whole profile, and the matric potentials at each depth, shown in Fig. 5.28, 5.29 and 5.30 respectively.

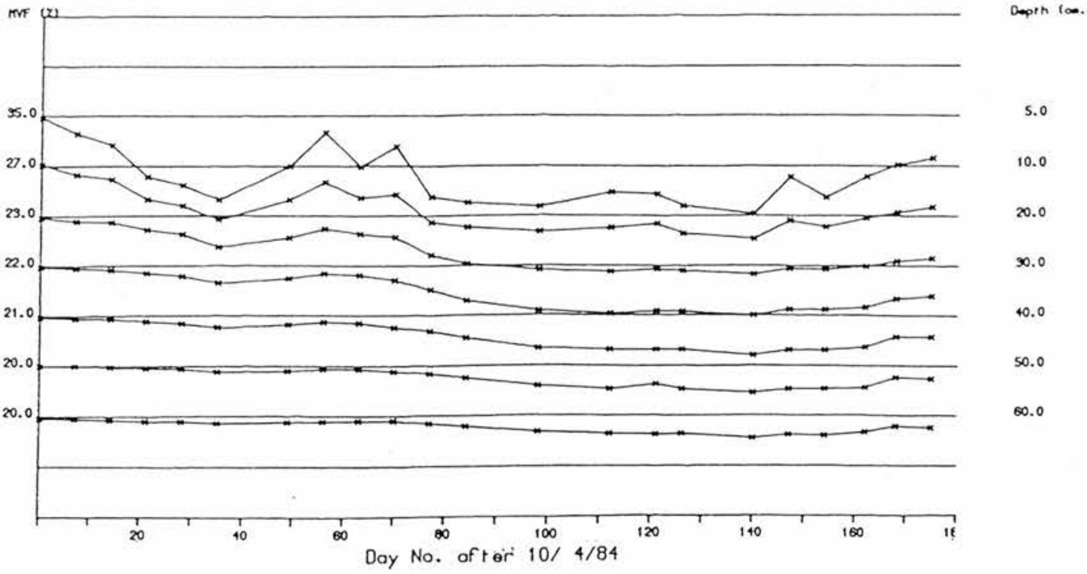


Fig. 5.28 Soil moisture content (%) at each depth - dry period 1984 (average of rows 1, 2 and 3)

Fig. 5.28 is the volumetric moisture content (in %), given as the average of three treatment rows. From the figure, it is possible to determine that within the top 40cm of the soil profile, significant changes in soil moisture content occurred, whereas below 40cm only small changes occurred. The most significant changes took place at 5 and 10cm depths especially between days no.49, 56 and 63 (29/5, 5/6 and 12/6) when the sharp increase resulted from the rainfall amount measured in these three weeks (88.9mm).

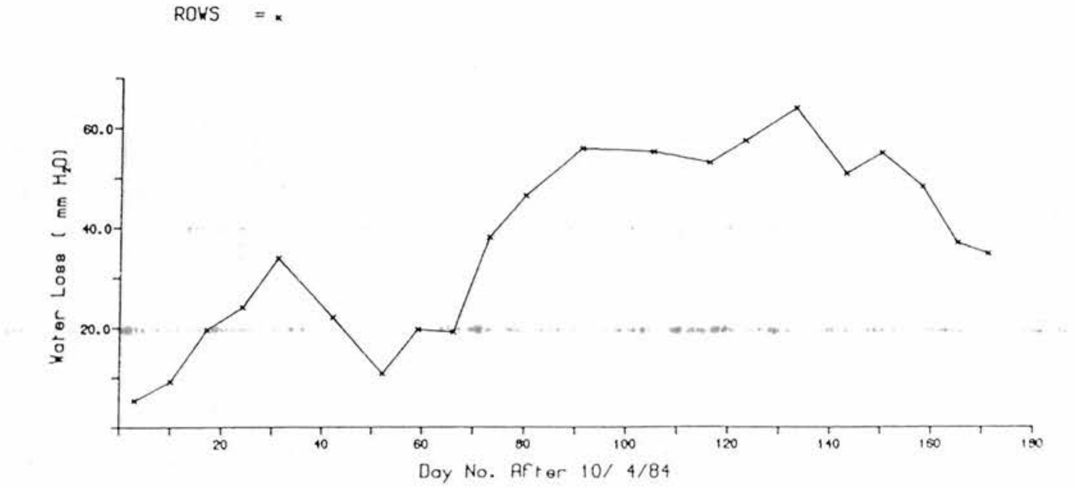


Fig. 5.29 Cumulative change in water content dry period 1984 (average of rows 1, 2 and 3)

Fig. 5.29 shows the cumulative change in water content, and the gain in soil water is visible between days no. 49 and 63 its subsequent loss as the soil dries out and the gradual recharge of the soil towards the end of the period can also be observed.

Fig. 5.30 shows the matric potential measured during the period at three depths, which show clearly that the soil profile dried out significantly to a depth of 25cm. Below this depth, apart from 14/8, the soil remained at comparatively high potentials. A rapid inspection of this figure permits the identification of a divergent zero flux plane (due to excess of cumulative evapotranspiration over rainfall) in the potential profile. The zero flux plane in the potential profile, marks the point where the potential gradient is zero. It determines the position of the divide between zones of upward and downwards flows of water within the soil. Thus, above 25cm, upward flows occurred to supply water depletion and below 25cm depth, water may have drained down to groundwater or may have been redistributed within the profile. This zero flux plane may of course, lie between the two points of measurement , ie between 10 and 25cm (see also p. 151).

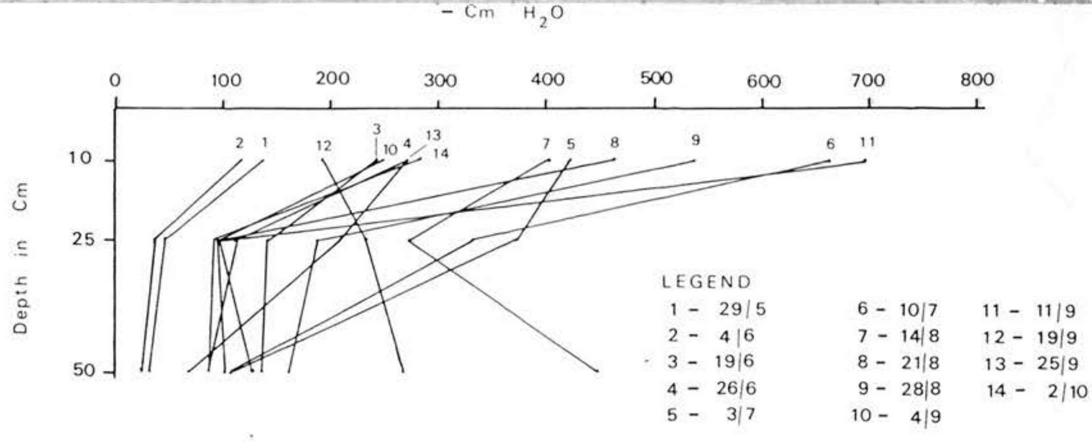


Fig. 5.30 Matric potential versus depth
Period May to October (1984)

Integration of the data from May to October 1984 (rainfall, runoff, evapotranspiration, change in soil water content) as a soil water balance is presented in Table 5.10, where the deep drainage is calculated using Eqn. 5.1.

Table 5.10

Soil water balance (millimetres)

date	prec.	average runoff	runoff std dev	AE	change in Sw	deep drainage
1 to 8/5	5.5	1.1	±1.0	14	-4.51	-5.09*
9 to 15/5	0.5	0.0	0.0	18	-9.79	-7.71*
16 to 29/5	41.0	8.0	±2.4	27	+11.78	-5.78*
30/5 to 5/6	28.7	4.6	±2.0	14	+11.36	-1.26*
6 to 12/6	19.2	2.8	±1.2	16	-8.9	+9.3 *
13 to 19/6	0.7	0.0	0.0	18	+0.51	-17.81
20 to 26/6	4.6	0.9	±0.1	21	-18.98	+1.68*
27 to 3/7	1.5	0.0	0.0	16	-8.31	-6.19*
4 to 17/7	10.0	1.0	±0.05	26	-9.33	-7.67*
18 to 31/7	18.7	6.1	±1.0	24	+0.67	-12.07
1/8 to 7/8	17.2	1.0	±0.7	13	+2.08	+1.12*
8 to 14/8	2.0	0.0	0.0	15	-4.31	-8.69*
15 to 28/8	1.9	0.0	0.0	20	-6.50	-11.60
29/8 to 4/9	34.3	7.4	±1.0	14	+13.15	-0.25*
5 to 11/9	4.6	0.0	0.0	13	-4.15	-4.25*
12 to 19/9	18.6	1.7	±0.7	7	+6.69	+3.21*
20 to 25/9	33.8	8.9	±1.0	11	+11.24	+2.66*
26 to 2/10	9.7	0.0	0.0	7	+2.23	+0.47*
total	252.9	43.5		294	-15.07	-69.53

* Not significant: below the total error of the soil water balance components.

precipitation error = ±20%
evapotranspiration error = ±10%
change in soil water error = ±2.7mm

Following the sequence of the measurements from Table 5.12, it is possible to see that during the week ending on 8/5/84, the rainfall total was 5.5mm. The average runoff was 1.1mm, mainly from the top gutter (B1) of plot B. The amount of deep drainage predicted for this period, 5.09mm, was not statistically significant. As shown in Fig. 5.28 and 5.29, loss of water occurred at the soil surface, probably due to evapotranspiration and the subsoil remained slightly below field capacity. The soil continued to dry out up to 15/5 as a result of the low rainfall.

Recharge of the soil moisture content due to rainfall, as shown in Fig. 5.28 and 5.29, started on 29/5, when soil reached values close to field capacity, and ended on 12/6.

This period is interesting because it shows a wet spell during the dry season, in which runoff occurred (Table 5.10) from the top soil gutters of the plots. The matric potentials (Fig. 5.30) indicate that the topsoil was drier than the subsoil (on 12/6 the matric potential of the whole profile fell below -850cm, thus tensiometer data is not available). Fig. 5.30 also indicates that flows were in an upward direction, from 25cm depth.

Assuming that runoff did not result from the precipitation rate being in excess of the soil infiltration capacity, that all soils have, without exception, a more permeable layer at the surface and that all rainfall entered the soil initially, it is possible to explain the observed runoff following the model depicted in Fig. 2.5 from Chapter Two. As the top soil was drier than the subsoil (Fig 5.30) flows of water may have moved laterally until high potential (greater than -100cm H_2O) was established between the surface and the subsoil layer, when percolation from the topsoil to subsoil may have occurred. During this period the soil may have reached field capacity; however, it is not possible to be certain about occurrence of deep drainage (12/6), as the estimated deep drainage was not statistically significant.

Due to low rainfall during the week ending on 19/6 the soil dried out and significant upward flows took place within the soil profile (Table 5.10).

In the week ending on 26/6, considerable depletion of soil water occurred (Table 5.10) to satisfy the evaporative demand of the period. The rainfall total was 4.6mm and the average runoff was 0.9mm, coming from gutters B1 and C1, while plot A collected flows in gutters A1 and A2. The potentials measured at either end of this period (19/6 and 26/6) show that the soil was still drying.

In the weeks ending on 3/7 and 10/7, data from tensiometers permit an evaluation of the depletion of the soil water (Fig. 5.30). When compared with the previous week, 26/6, the soil in these weeks was considerably drier, especially close to the surface and it is clear that during this period, flows were in upward direction due to soil water abstraction as the evaporative demand was not satisfied by the rainfall. No runoff was measured over the two weeks.

From 10 to 17/7, the rainfall total was 10.0mm and the average runoff was 1.0mm collected in gutters B1, C1 and A1 and A2. The soil remained dry until 31/7, preventing tensiometer measurements, although in the middle of the period there was a rainfall event of 18.6mm. The runoff collected from this rainfall amount was 6.1mm collected in gutters B1, C1 and A1 and A2. This and the previous period

(10 to 17/7), are examples of runoff generation when the soil was dry, and presumably with a matric potential gradient within the profile. Again in this circumstance, the assumption is that water infiltrated and, due to the differences in potential between the organic and mineral soil, took a lateral flowpath, obeying the model shown in Fig. 2.5 (Chapter Two).

In the week ending on 7/8, the dry soil conditions were still affecting the tensiometers preventing readings from being taken. A rainfall amount of 17.2mm was measured, generating an average runoff of 1.0mm measured in gutters A1, A2, B1 and C1. In this period, the runoff amount had decreased when compared with the previous period, suggesting that during this occurrence more uniform water potentials were present in the soil inhibiting the lateral runoff. A slight gain in soil water or deep drainage (or redistribution of water) in the profile is shown in Table 5.10.

The tensiometers returned to working condition in the week ending on 14/8, however the results for this period appear suspicious, especially at 50cm depth. The large decrease in soil water potential at 50cm depth is much lower than any other observation, before and after this date. The potentials on 10/7 and 21/8 are very similar and high (-100cm H_2O) compared with the value of -450cm on this date (14/8). This represents a change in MVF (moisture volumetric fraction) of 5% (Fig. 5.27) no such change occurred during this period. It is possible that this result was due to a problem in recharging the tensiometers. This is reinforced by the variability of the potential results on this date -109cmH_2O compared with the average error of −45cm H_2O.

The weeks ending on 21 and 28/8 were analysed together, since the neutron probe measurements at this period were taken at two week intervals. The rainfall accumulated was only 1.9mm and no runoff or deep drainage occurred. In the absence of rain, soil water was lost from the soil as shown in Table 5.10.

The matric potentials close to the surface during the period 15 to 28/8 decreased in relation to the week ending on 14/8. In the lower horizons the indication is that they were wetter, despite the low rainfall amount, suggesting the possibility of accumulation of moisture from upslope, as observed by Atkinson (1978). There is only one line of evidence to support this argument, which is the fact that the tensiometers upslope were very dry (although recharged simultaneously with the face tensiometers, most of the upslope tensiometers were not working). This could be interpreted to suggest that water was moving from upslope to the face of the profile.

From the 28/8 to 4/9, 34.3mm of rainfall was measured and this increased the soil water content, especially in the surface (Fig. 5.28) the soil water potential increased as shown in Fig. 5.30. The average runoff was 7.4mm, collected from gutters B1, C1, A1 and A2. Again, this is an example of runoff occurring when the soil was dry, and a matric potential gradient existed between the top and subsoil layers. From Table 5.10 it can be seen that the soil gained water which did not percolate, but was used to recharge the soil moisture content.

In the week ending on 11/9, a very low amount of rainfall (4.6mm), resulted in a loss of soil water, especially at 10cm (Fig. 5.30), while the lower soil layers remained wet.

Rainfall accumulating in the period ending on 19/9 amounted 18.6mm, exceeding evapotranspiration. This increased the soil water content, mainly at 5cm depth (Fig. 5.28 and Table 5.10). The large increase in potential (Fig. 5.30) especially at 10cm depth, was probably not valid, as the tensiometers had been recharged less than 24 hours earlier, and consequently, at least on the surface, the tensiometers probably did not have time to equilibrate with the soil water. The runoff amount collected was 1.7mm from gutters A1, B1 and C1.

During the week ending 25/9, the total rainfall amount 33.8mm again increased the soil water content (Fig. 5.28 and Table 5.10).

In Fig. 5.30, on that date, it is possible to see an increase in the potentials when compared with previous reading (11/9). However, the potentials measured upslope, especially at 10cm, appear to be in better agreement with the rainfall amount, than those measured at the face of the profile. Fig. 5.31 shows the potentials measured upslope of the plots:

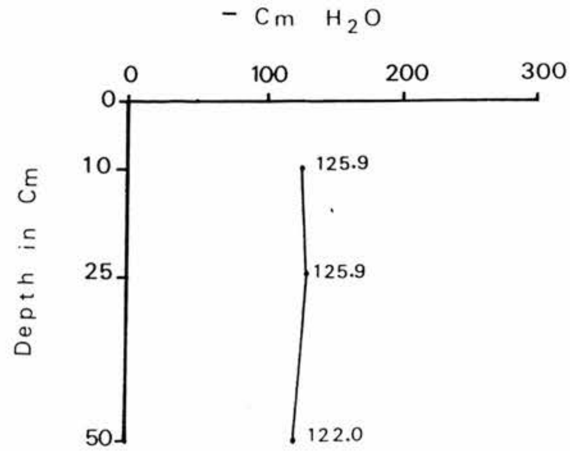


Fig. 5.31 Matric potentials for upslope tensiometers (25/9)

Comparing the surface values of the potentials, it is clear that the surface horizon of the artificial face was subjected to more variation in its water potential, whilst at 25cm and 50cm there was a better agreement with the upslope tensiometers and the variability reduced. This indicates a more uniform distribution of soil matric potentials at these depths. As this problem only occurred between tensiometers located close to the surface, and not at lower depths, where tensiometers showed a reasonable agreement, there was no valid reason to reject the data from the exposed face. This decision may introduce an error when determining the direction of the flows within the surface layer. However, this problem will not happen below 25cm depth as can be inferred from Fig. 5.30 and 5.31.

The average runoff for this period was 8.9mm collected in gutters A1, A2, B1 and C1.

For the week ending on 2/10 the soil water content increased slightly in response to 9.7mm of rainfall. The potentials at the surface layer did not indicate this increase, although at 25cm and 50cm depth the tensiometers measured an increase in the matric potential. The tensiometers upslope when compared with the face tensiometers were drier at 25cm and 50cm depth, suggesting movement of water towards the face of the profile, as shown in Fig. 5.32.

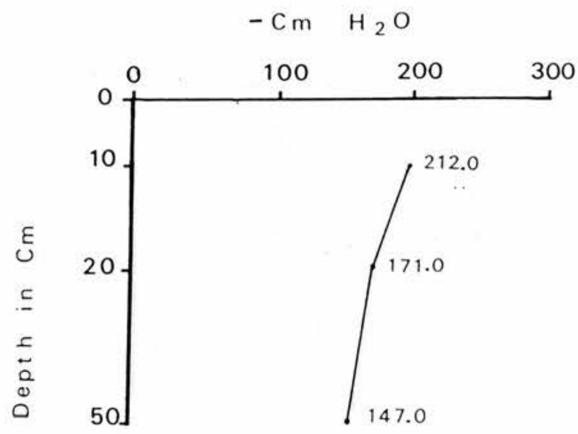


Fig. 5.32 Matric potentials for upslope tensiometers (2/10)

As it can be inferred from Fig. 5.30 (earlier), flows of water were in upward direction at the surface and below 25cm depth only a slight downward movement occurred. Runoff from the plots did not occur.

Discussion

Reviewing the events during this period it is possiible to see that the soil was kept dry most of the time, due to abstraction of water to satisfy the evaporative demand of the period.

It is worth mentioning that, although the soil was at moisture deficit (see Table 5.5 earlier), runoff occurred in the wet spells which did not return the soil to field capacity but only lowered the cumulative moisture deficit. That runoff occurred when there was a soil moisture deficit, contradicts the assumption of Zaslavski and Sinai (1981) who postulated that runoff occurs only after a cumulative effect of rainfall in the soil. In other words no runoff occurs before a few hundred millimetres of precipitation have fallen. Putting this in another way, according to this assumption, the soil would have to recover its field capacity status to start producing runoff. In the current experiment, runoff occurred when the soil was below its field capacity, as it had been observed by Baloutsos (op.cit) and Thompson (op.cit). Runoff occurred from rainfall amounts equal to or above 4.6mm, and it appears that the control factor for runoff generation was the presence of a potential gradient within the soil profile.

As shown in Table 5.10, during this period it is doubtful that any 'summer percolation' had occurred, since the deep drainage values are below the cumulative error of the water balance components.

It is also worth noting the presence of a divergent zero flux plane (Fig 5.30) in the soil profile, dividing upward and downward flows of water as observed by McGowan and Williams (op.cit). From the determination of the zero flux plane, it is possible to see that the soil zone above 25cm has flows in an upward direction and that it supplies the demands of evapotranspiration. Below 25cm depth, the fluxes are in downward direction, representing either redistribution of water or drainage to the groundwater. A comparison between drying depths inferred by the neutron probe measurements (Fig. 5.28), with those inferred by potential measurements, shows that the drying depth inferred by the probe is deeper (40cm). These differences can be attributed to the fact that tensiometers were installed only at three depths and none were installed at 40cm.

However, despite this difference in drying depths, the presence of a zero flux plane in the soil profile confirms that once roots have begun the depletion of soil water, percolation from that soil horizon, unless rewetted, will have ceased (cf McGowan and Williams, op.cit).

This identification of a zero flux plane, separating zones in the profile, where for example flows are in upward direction, is important in the context of the current research. It reinforces the assumption that when the soil is dry, lateral water movement in the surface will dominate over vertical movement until a sufficiently high water potential is reached to cancel out the zero flux plane. As it was reported earlier, all runoff events occurred from the top soil horizon when it was visibly drier than the subsoil.

Results of the wet period of 1984

Following the criteria outlined earlier to define dry and wet periods, it is possible to consider the middle of October as the time when soil started returning to field capacity, thus marking the beginning of the wet period of 1984. Analysis of the weekly soil water balance covers the period on 9/10 until 31/12, when field work was interrupted due to cold weather conditions which prevented the use of tensiometers and also made access to the site difficult.

The changing moisture conditions are illustrated by Figs. 5.33 and 5.34 and summarized in Table 5.11. The soil moisture content in each layer is shown in Fig. 5.33, whilst Fig.34 depicts the change in water content in the soil profile.

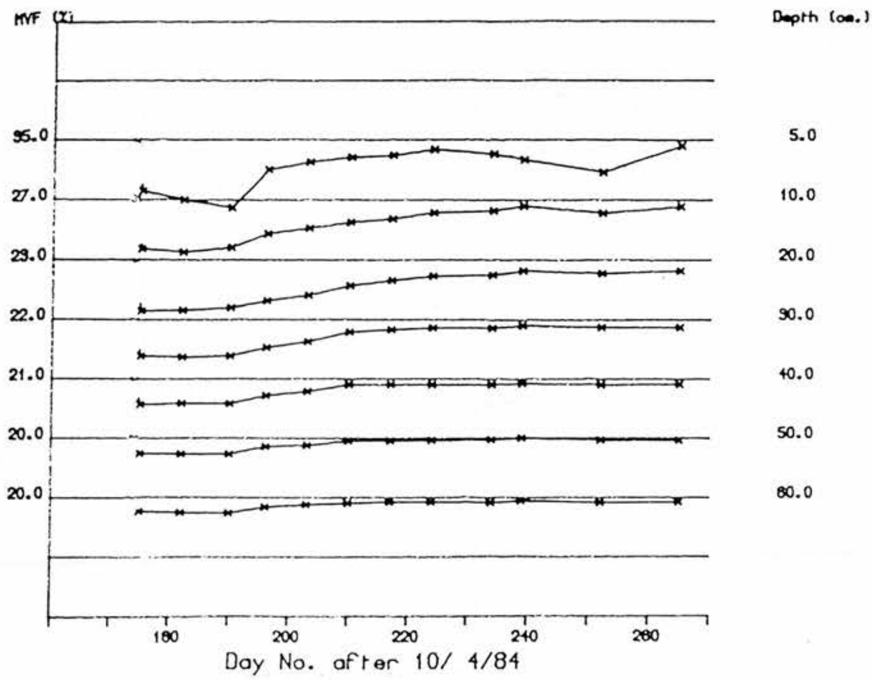


Fig. 5.33 Soil moisture content (%) at each depth
wet period 1984
(average of rows 1,2 and 3)

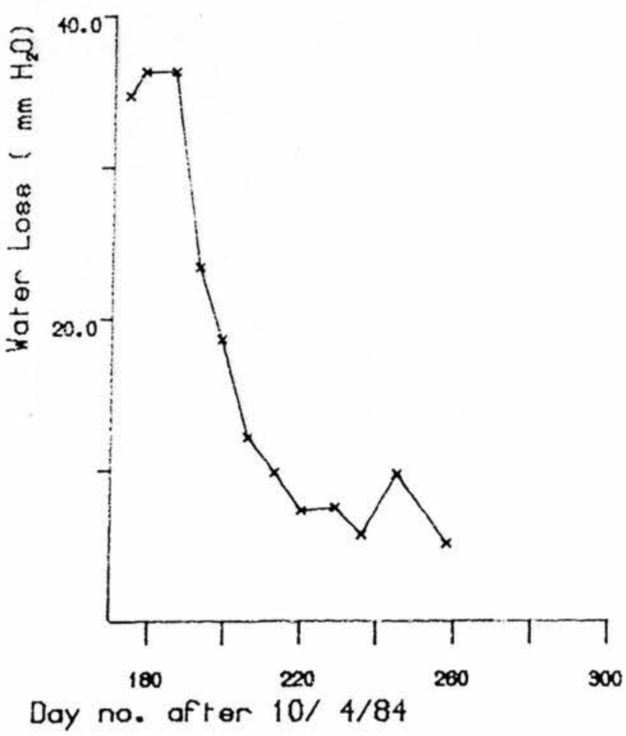


Fig. 5.34 Cumulative change in water content
wet period 1984
(average of rows 1,2 and 3)

The soil water potentials are presented in Fig. 5.35, and show a general increase in the potentials as the soil returns to field capacity. The absence of zero flux plane, because the potentials were uniform during this period, gives an indication of the predominance of downward flows of water.

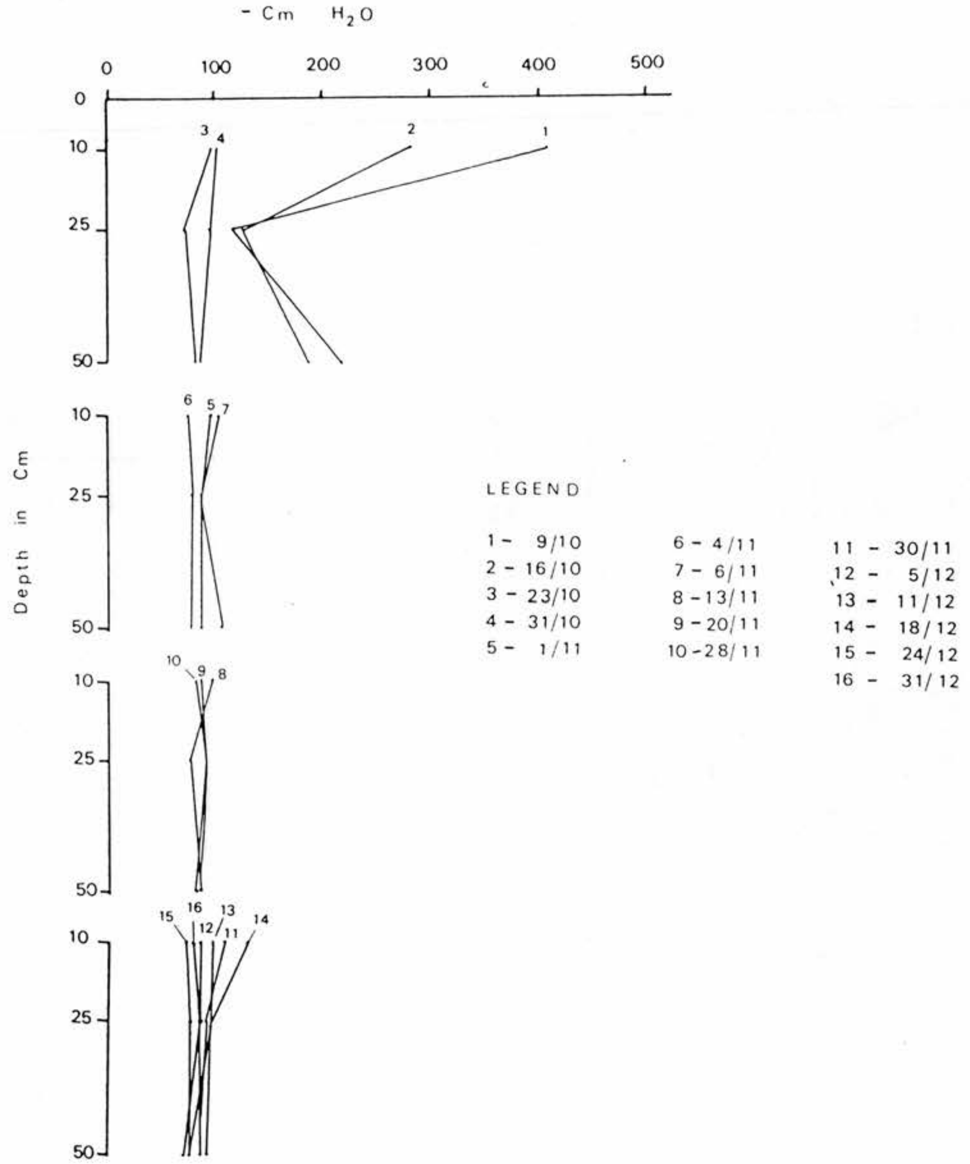


Fig. 5.35 Matric potential versus depth measured in the wet period 1984

The data for the soil water balance is shown on Table 5.11:

Table 5.11

Soil water balance (millimetres)

date	prec.	average runoff	runoff std dev	AE	change in Sw	deep drainage
3 to 9/10	4.0	0.0	0.0	8	-1.59	-2.41*
10 to 17/10	7.8	0.0	0.0	8	+0.02	-0.22*
18 to 23/10	26.5	3.0	±1.3	8	+12.81	+2.69*
24 to 31/10	31.0	4.8	±1.0	6	+4.86	+15.34
1 to 6/11	113.0	29.5	±4.3	6	+6.46	+71.04
7 to 13/11	44.8	3.5	±1.6	3	+2.30	+36.0
14 to 20/11	19.5	0.0	0.0	3	+2.57	+13.93
21 to 30/11	31.6	4.6	±1.4	5	-0.20	+22.20
1 to 5/12	21.0	0.0	0.0	4	+1.78	+15.22
6 to 18/12	13.9	0.0	0.0	6	-4.00	+11.90
19 to 31/12	25.7	0.0	0.0	5	+4.59	+16.11
total	338.8	45.4		62	29.6	201.80

* Not significant: below the total error of the soil water balance components.

precipitation error = ±20%
evapotranspiration error = ±10%
change in soil water error = ±3.1mm

A rapid comparison between the data shown in this table and Fig. 5.35 shows that runoff decreases or ceases as the potential gradients decrease within the soil profile. This means that, although the soil is wetter than during the previous periods, the runoff quantity at the end of this period is only marginally higher than that measured previously. As shown in Table 5.11, most of the water was lost as deep drainage, since the evaporative demand over the period was low. The predominance of vertical water movements is not in fact surprising in the presence of uniform matric potentials. In addition, there was no differentiation in the soil profile in terms of the existence of a fine textured layer rich in clay (Table 3.1, Chapter Three), which could act as an impeding layer for downward movements of water. As shown earlier (Fig. 5.27),this soil has a significant number of large pores which leads to rapid vertical drainage and no textural differences down the profile (Table 3.1). Using the value of the hydraulic conductivity of 35cm/day and the potential gradients measured, it is posssible to accept the high quantities of water lost as deep drainage.

In the week ending on 9/10, the soil had dried slightly at the surface, as shown in the Fig. 5.35 and Table 5.11 and it can be inferred that the direction of the flows was upward above 25cm depth and downward below 25cm depth. Runoff did not occur in this period.

In the next period soil water measurements were made 24 hours after tensiometer reading, i.e. on 17/10 instead of 16/10. For this reason the tensiometer data can only be used as a rough guide for comparisons with the soil water content.

From Table 5.11 it is possible to see that the soil water content remained practically unchanged. Although the rainfall amount was distributed in two events (10/10) at the beginning and in the middle (13/10) of the period, there was an increase in the potential at 10cm depth, which suggests that water had moved down to lower layers. From the data on Fig. 5.35, it is possible to infer that flows were in upward direction close to the surface and in downward direction below 25cm depth. From 17 to 23/10, the total rainfall accumulated was 26.5mm, considerably increasing the soil matric potential due to water infiltrating down the soil profile. Any flows were slightly upward in the surface with slight downward movement below 25cm depth. Runoff collected was 3.0mm (average) coming from gutters A1, B1 and C1.

The rainfall accumulated in the week from 24 to 31/10 was 31.0mm, slightly increasing the soil water content (Table 5.11) and keeping the potentials practically unchanged since the last observation (the only change occurred at 25cm depth). Again the potentials were uniform indicating drainage through the soil profile and from the soil water balance this was 15.3mm (Table 5.11).

In the week ending on 6/11, the total rainfall accumulated from 31st October was 113mm, the highest total rainfall for 1984. Most of this precipitation occurred on the 3rd November with aproximately 81mm accumulated in the 24 hours (9:00 3rd November to 9:00 4th November) which is considered to be the 20 year storm for south east Scotland (D.C. Ledger, personnal comm.). During this period, on many occasions rainfall intensities in excess of 8mm hr^{-1} were recorded by the Meteorological Department of Edinburgh University, at their Kings Buildings location. This heavy rainfall resulted in flooding in areas of Edinburgh due to excess of stream and drain flow. In view of the excessive quantity of precipitation, the study site was visited on the 4th November to record rainfall, runoff and tensiometer results. Thus, of the 113mm of rain accumulated for the entire period, 110mm had been collected by 4th November and 29.5mm of runoff was measured from gutters A2, A3; B1, B2, B3; C1, C2 and C3. This runoff amount was the highest of the season and its occurrence can be attributed to the heavy rainfall events of the period.

From Fig. 5.35, it is clear that the intense rainfall of 3/11 resulted in a slight increase in the matric potential, but most noticeable is the degree of uniformity of the matric potentials down the soil profile, which led to the predominance of downward flows of water. As it has already been pointed out, although the runoff was the highest for the field season, a much higher quantity of water was lost as deep drainage (Table 5.11). In terms of percentage of loss of water for the whole week, runoff accounted for 26% of the rainfall and loss through deep drainage accounted for 62%. Evidence of the importance of deep drainage in the study site is given in Table 3.2 (earlier in Chapter Three) which reveals the low amounts of exchangeable cations remaining in the soil profile due to leaching. Verification of this high level of deep drainage amount can be achieved using the estimated hydraulic conductivity (35cm/day) and the hydraulic potentials measured on 4/11. The results indicated that this could move up to 357.5mm of water per day, which shows that the high deep drainage value calculated by the soil water balance is acceptable.

The picture concerning the distribution of water potentials for the week from 6 to 13/11 is quite similar to the last readings, with possibly a slight upward movement above 25cm and downward flows below 25cm. This is to be expected since the soil was almost freely draining under gravity. Again, due to this degree of uniformity of matric potentials in the soil profile, downward movement of water prevails over lateral runoff which accounted for only 3.5mm of the rainfall amount. This runoff amount was collected in gutters A1, A2; B1, B2 and C1.

From 13 to 20/11, the soil water potentials remained the same as in the previous week, implying that most of rainfall was lost through deep drainage (Table 5.11), and in fact, no runoff was measured.

From 20 to 30/11 (matric potential and precipitation measured on 28/11), the rainfall accumulated was 31.6mm and there was only a minor change in the soil water content. As shown in Fig. 5.35, the top soil is still increasing its water content, and layers below 30cm reached field capacity, reaching their limit in terms of capacity for storing water against gravity.

From the potentials shown in Fig. 5.35, it is possible that soil water content may have increased, since of this 31.6mm of rainfall, 22.8mm fell between 9:00 26 November and 9:00 27 November. However, by 30/11, there was a slight but not significant decrease, in soil water content at

10cm, compared with 28/11, as the rainfall amount betweeen 28-30/11 was only 0.5mm. This observation is in agreement with the decrease in potential at 10cm.

As the soil was at field capacity at that time, it was to be expected that there would be no significant changes in soil water as any excess water would result in drainage out of the profile. From the matric potentials, it is reasonable to infer that flows were moving slightly in a downward direction. Runoff accumulated from 20-28/11 averaged 4.6mm, with flows collected at gutters A1, A2, A3; B1, B2, B3; C1, C2, C3 which indicates that soil may have reached saturation(especially in lower horizons). Again however, deep drainage prevailed over runoff, accounting for 22.2mm of water (Table 5.11). No runoff occurred between 28-30/11.

For the next period, the results obtained for the whole of December 1984 will be presented. The total rainfall accumulated in December 1984 was 58mm, as shown earlier in Table 5.1 and there was no runoff from any of the plots. During this period regular checks of the gutters and the plastic pipes were made, and there was no evidence of ice blocking the gutters or the plastic pipes, thus preventing collection of any runoff. In view of this, the absence of runoff in these weeks must be attributed to the low intensity of rainfall (see Table 5.12), and the uniform matric potentials within the soil profile resulting in downward flow of water.

Table 5.12

Rainfall intensity duration
for December 1984

INTENSITY mm/hr	duration in hours							
mm	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
0.1 - 0.2	1	4		3		1	3	
0.3 - 0.5	4	1	1				1	
1.0 - 1.1	1		1	1				
1.2 - 2.0		1		1				1
2.1 - 2.3			1					

Note: numbers are the frequency of events

From Table 5.12, it is possible to see that during none of the rainfall events was precipitation accumulating in the rain gauge at a rate in excess of 2.5mm hr^{-1} . This indicates that no 'storms' (greater than 4.0mm hr^{-1}) were observed during December 1984, using the classification of types of rain as given in Plant (1968). In fact most of the precipitation fell as slight rain (less than 0.5mm hr^{-1}) and only a few events could be classified as moderate rain (0.5 -4.0mm hr^{-1}).

The soil, in particular at the surface, showed an increase in soil water. As the lower layers were already at field capacity and the surface layers were at or near field capacity, any significant increase in soil water would drain away. The potentials measured on 5/12 showed that the profile was uniformly wet.

The rainfall accumulated on 18/12 (two periods added together) was 13.9mm, and of this 9.4mm fell before 11th December, and 4.5mm up to 18th December. As the major quantity of rain fell in the first week the matric potentials were kept high and uniform, whereas a slight decrease occurred on 18th, especially at 10cm depth. No changes in matric potential occurred at 25cm and 50cm depth. The change in soil water content at 10cm was detected by the neutron probe (Fig. 5.33) but any change at 50cm was too small to be detected. From Fig. 5.35 it is possible to infer that until 11/12, water was moving down the profile, whereas by 18th water was only draining from below 25cm, and there appears to be a slight upward movement above this depth.

For the last two weeks of December (weeks ending on 24th and 31st), the total rainfall accumulated was 25.7mm with 19.5mm falling in the first week and 6.2mm falling in the second. The matric potentials increased and their uniformity shows quite clearly that water flows were controlled by the gravitational potential.

From the data for December 1984, it is thus possible to infer that low intensity and low total volume of rainfall falling on a soil, without major textural discontinuities, at or near field capacity, results in deep drainage through the profile with no significant lateral runoff occurring (Table 5.1).

Discussion

Examining the entire first season (dry and wet periods), it can be observed that the dry period was characterized by the presence of moisture potential gradients in the soil profile which determined the occurrence of lateral flows of water, obeying the mechanism of flows in dry soils exemplified earlier in Fig 2.5 (Chapter Two). The existence of such differences in matric potentials within the profile also determined the presence of a divergent zero flux plane, which allowed the distinction of the zones where upward flows or redistribution of water took place within the profile. Support for the hypothesis, that in the dry period, water was redistributed laterally within the soil profile, is given by the evidence in Fig. 5.8 (Cumulative change in water content, earlier in this chapter), where the four rows of access tubes are ranked according to their position in the slope. For instance, row 4, the lower row on the slope, is wetter than the other three rows.

As the soil moisture is gradually recharged, in the wet period, the difference between rows tends to be insignificant (Fig. 5.14) as the soil becomes uniformly wet. This condition is also reflected by the gradual disappearence of the zero flux plane in the soil profile, which indicates that in the wet period vertical flows of water prevail over lateral flows. This behaviour of the water flows for such a coarse textured soil without an impeding layer, is in agreement with observations of Atkinson (op.cit) and Dunne (op.cit).

The assumption that matric potential gradients are an important control factor in runoff generation, in this type of soil, permits one to postulate that runoff is mainly confined to the dry period (soil below field capacity). This follows the observation that there were eleven runoff events in the dry period (Table 5.10) against only four in the wet period (Table 5.11). As well as generating more runoff events, the fraction of precipitation that resulted in runoff in the dry period was higher than that in the wet period. In fact, the total rainfall for the dry period was 252.9mm and the runoff was 43mm, whereas in the wet period rainfall was 338.8mm and runoff 45mm, only marginally above the amount collected in the dry period.

It is also possible to infer that, if matric potential gradients are the main control factor for runoff generation, the flow quantities can be expected to be low (as shown in Table 5.10 and 5.11). This is because these gradients will disappear as the soil profile becomes uniformly wet, giving rise to downward movements of the water and also the volume of precipitation is generally lower in the summer.

However, in heavy rain events (and possibly in the presence of a matric potential gradient within the profile) runoff (surface and subsurface flows) can be significant. This is exemplified in the 20 year storm such as the one observed in November 1984. Such an event indicates that a hillslope may generate, on most occasions during gentle storms, low quantities of either subsurface flows or deep drainage or both and Hortonian overland flow during a 'deluge' (Dunne, 1983).

As can be deduced from Tables 5.10 and 5.11, the variations between the runoff results range from 5% to 90%, and are only of similar order of magnitude in the weeks ending on 29/5, 5/6 and 12/6. The existence of variations between the runoff results implies that individual plots do not have a consistent response from event to event, and this variability could be taken as a criterion in the design of a runoff-rainfall model to predict mean runoff during each rainfall event.

Variations between runoff results from plot experiments are not uncommon, as already shown by Arnett (op.cit) and Hjelmfelt and Burwell (op.cit). In this particular experiment with three very close small plots, it is possible to exclude differentiating factors such as vegetation cover, angle of slope, altitude, rainfall amounts and intensities as causes for variability between plots. Therefore, it is suggested that this variation between runoff amounts must be attributed to natural variability within the plots (e.g. different matric potential gradients, preferential flows down the macropores etc) which, though similar between plots, may be located at different positions within each of the plots.

The interesting point in the observed runoff variability is that these variations were large, occurring between nearly adjacent plots. However, although, variation occurred in the scale of very close small plots, implying that conditions such as matric potential gradients should be investigated in greater detail, the present plot replicates may be used to predict runoff. This is shown by the similar temporal pattern of the runoff events (Fig. 5.2 earlier) and by the reasonable accuracy of the regression models (coefficients of determination of 30.3%, 22.2% and 52.1% for plots A, B and C respectively). Such results obtained for plots of 0.81m permit recommendation of plots of similar size for predictive approaches. Further, as the results were similar to those attained by Anderson et.al (op.cit), they contradict the recommendation proposed by those authors concerning the need of using plots greater than $3m^2$, for predictive approaches.

Considering the behaviour of the soil water over the 1984 field season, it appears that 'a priori', these results do not support either Horton's or Hewlett's models about the disposition of the water over hillslopes in humid climate, at least to a depth of 60cm. Thus, to this depth, the results appear to be in better agreement with the model proposed by Burns (op.cit) with the upward movement of water in the dry period, occasional runoff and deep drainage in the wet period.

However, it is not possible to discard Hewlett's proposition about the disposal of water over hillslopes following a subsurface flow path, due to the possibility that below the depth investigated, water may encounter a less permeable layer, which after reaching its saturation, will determine a subsurface lateral flowpath. Following Hewlett's ideas, this water will move downslope displacing previously stored water (transient flow) towards the stream. This supposition that water may have been diverted, flowing parallel to the slope can be supported by evidence given by Dunne (1978) about the occurrence of subsurface flows, recorded in a plot experiment on well drained hillslopes, between 0.6m and 2.1m depth.

Evidence of a saturated wedge at the foot of the slope down the study site, on poorly drained soils, suggested that flows of water may follow a subsurface route along that slope, emerging at the saturated wedge and running over the surface as saturated overland flow. The presence of this saturated wedge at the foot of the slope, which expands in wet periods and retracts in the dry periods, is evidence supporting the variable source area and the subsurface flow concept in the study area.

At present, with the data available from the study site (in a rectilinear segment of the middle of the slope), it is only possible to state that to the depth investigated, flows of water in the dry period occur close to the surface obeying a preferential lateral potential gradient in agreement with observations of Hewlett and Troendle (op.cit). During the wet period, lateral flows cease, giving rise to vertical flows controlled by the gravitational potential in agreement with observations by Atkinson (op.cit) and Dunne (op.cit). Therefore, in order to confirm Hewlett's model, the present experiment would need expansion. This could focus on the study of the potentials in saturated conditions, with a grid of tensiometers installed over the slope particularly on the footslope to provide a map of the moisture conditions. The installation of tensiometer nests positioned vertically in selected profiles would provide information on the soil potential. The experiment could also include hydraulic conductivity determinations to give soil moisture velocities. This would provide information on the expansion and contraction of the source area and information about the slope discharge hydrograph.

Finally, referring to the data on deep drainage (Table 5.10 and 5.11), it is possible to see that no significant values of deep drainage occurred during the dry period. Significant values of deep drainage started only in the 'wetting season', when the root zone was building up its storage from water in progressive downward movements of the wetting fronts of infiltration in sucessive rainfall events. Looking at Table 5.11, it appears that the process of replenishing the soil pores in this first field season took approximately two weeks, to allow the first significant downward movement of water to occur.

Results for the second field season - 1985

Observations in the second season comenced in May; no earlier data could be obtained due to adverse weather conditions.

As shown earlier (Fig. 5.5, 5.6 and Table 5.5), this field season had a very short 'dry' period when compared with the entire field season of 1984. On most occasions, soil water potentials and soil water content remained at or near field capacity indicating that there were negligible soil moisture deficits. In view of this, it was decided to analyse the field season of 1985 as a single wet period, as the only noticeable moisture deficit occurred in June (Table 5.5) and the soil had returned to field capacity by the end of July (Fig.5. 5).

Fig. 5.36 shows the soil moisture content through the soil indicating again, that major soil water losses only occurred above 40cm, and that below this depth only small changes took place.

Fig. 5.37 shows the cumulative change in water content as an average of the upper three access tube rows.

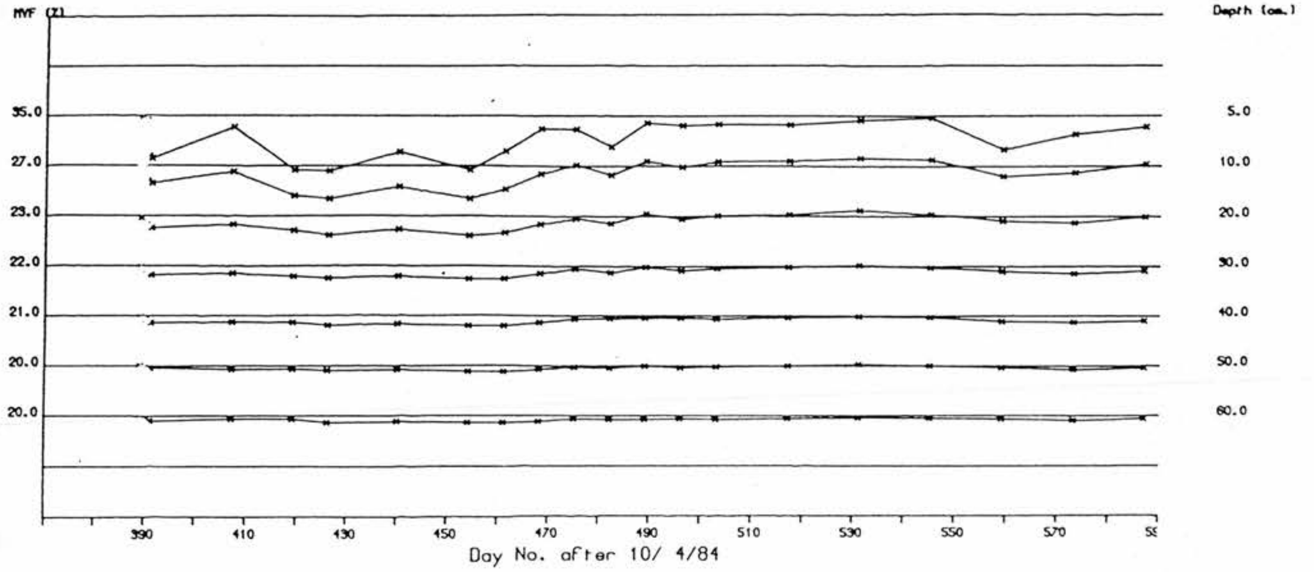


Fig. 5.36 Soil moisture content at each depth
Period May to November 1985

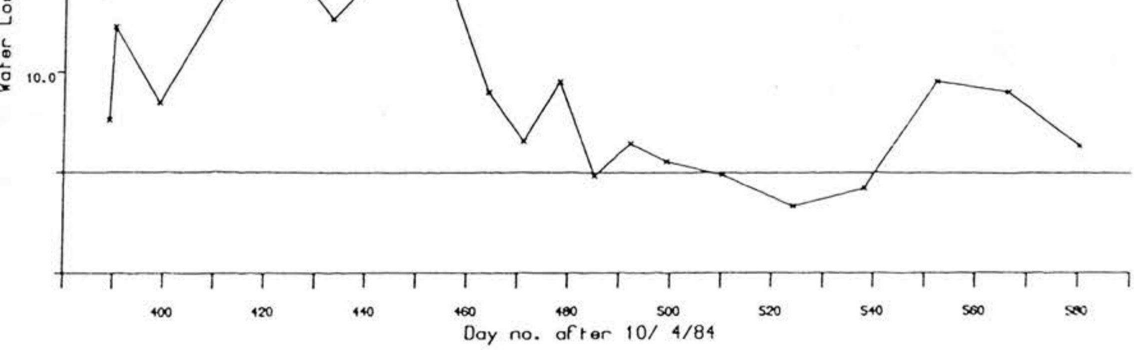


Fig. 5.37 Cumulative change in water content
Period May to November 1985

Matric potentials measured during the period are shown in Fig. 5.38,where it is noticeable that, due to the high water content of the soil at the surface, there was a convergent zero flux plane (i.e. flows of water moving from the surface down into the profile) over most of the time. A clear divergent zero flux plane (i.e. flows moving in upward direction from a given depth in the soil profile), was only apparent in June (18/6) when the soil was under a moisture deficit. However, as the soil water was recharged by rainfall, a convergent zero flux plane prevailed and towards the end of the season the point of inflexion at 25cm depth disappeared, thus re-establishing drainage down the profile.

Data for the analysis of the weekly soil water balance is presented below in Table 5.13. A rapid glance at this table permits one to see that, apart from contrasting with the 1984 in terms of high soil water content, this period also contrasts in terms of its low runoff quantities.

Comparing the runoff occurrences in this table with the matric potentials, it is possible to observe that runoff was occurring when there was a potential gradient in the soil profile. The data also reveal that the runoff accumulated by the end of the period, was less than half the total accumulated in each period of the first field season, in spite of the high rainfall events that occurred during the second field season.

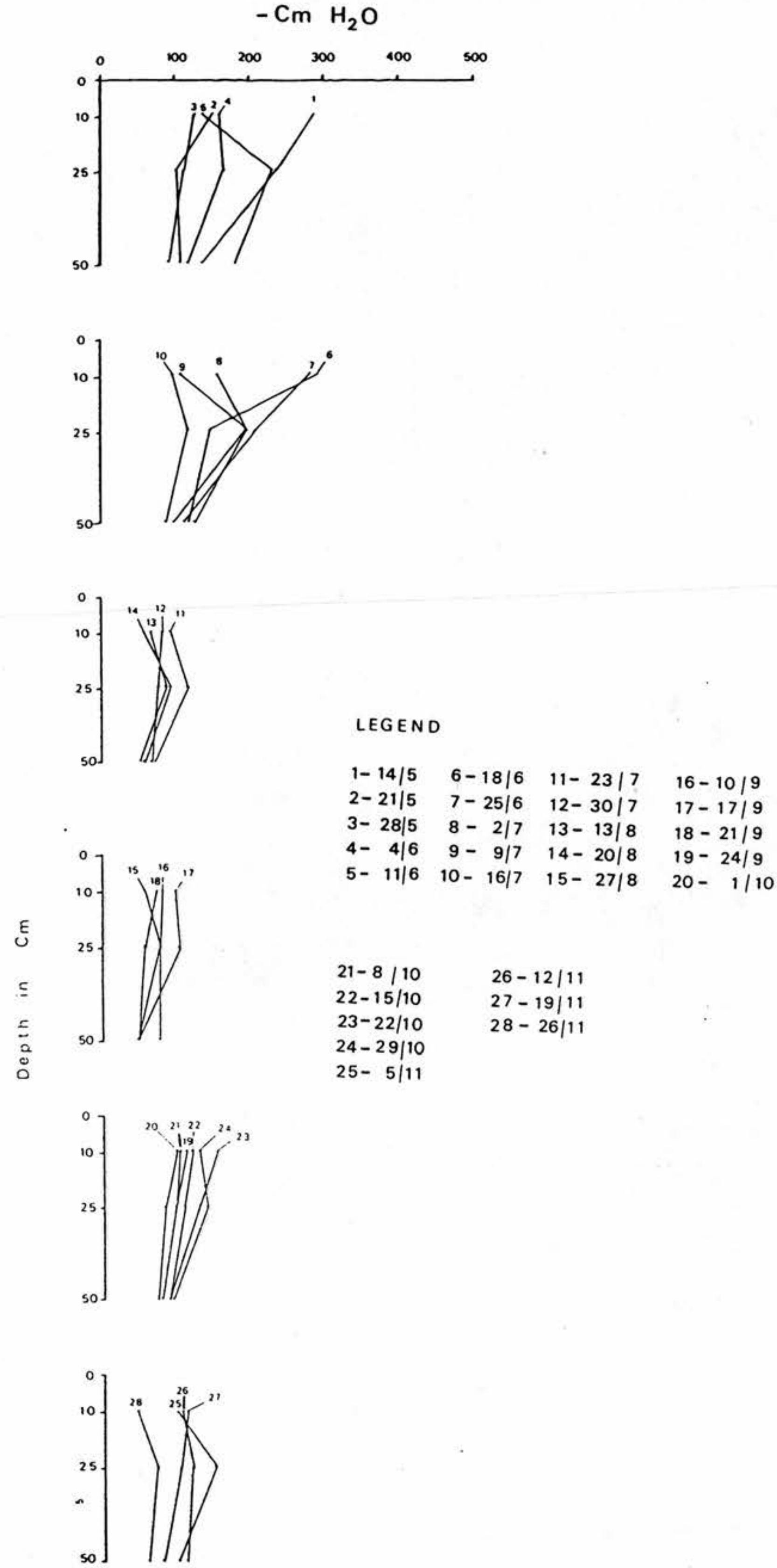


Fig. 5.38 Matric potential versus depth. Period 14/5 a 26/11/85

Table 5.13

Soil water balance (millimetres)

date	prec.	average runoff	runoff std dev	AE	change in Sw	deep drainage
30/4 to 7/5	2.0	0.0	0.0	14	-5.23	-6.77
8 to 23/5	34.6	1.0	±0.4	22	+7.60	4.00*
24 to 4/6	20.2	0.0	0.0	40	-12.08	-7.71*
5 to 11/6	10.1	0.0	0.0	15	-3.43	-1.47*
12 to 25/6	39.7	3.2	±2.0	30	+7.04	-0.54*
26/6 to 9/7	24.8	0.4	0.2	31	-6.42	0.82*
10 to 16/7	22.6	3.0	±1.0	17	+4.06	-1.46*
17 to 23/7	31.0	2.0	±1.4	18	+9.76	1.24*
24 to 30/7	128.7	11.0	±6.7	11	+4.99	101.86
31 to 6/8	9.0	0.0	0.0	18	-5.99	-3.01*
7 to 13/8	20.0	0.4	±0.2	18	+9.22	-7.62*
14 to 20/8	20.0	0.0	0.0	12	-3.19	11.19
21 to 27/8	26.5	0.0	0.0	17	+1.87	7.63*
28/8 to 10/9	46.5	0.0	0.0	19	+3.4	24.10
11 to 24/9	127.0	0.15	±0.1	21	+0.5	105.3
25 to 8/10	41.7	0.0	0.0	20	-0.9	22.6
9 to 22/10	5.0	0.0	0.0	9	-11.2	2.2
23 to 5/11	12.5	0.0	0.0	8	+2.4	2.1*
6 to 19/11	23.7	0.0	0.0	7	+6.4	10.3
20 to 5/12	40.0	0.8	±0.9	6	+5.7	27.5
total	685.6	21.05		353.0	15.4	297.25

* Not significant: below the total error of the soil water balance components.

precipitation error = ±20%
evapotranspiration error = ±10%
change in soil water error = ±3.1mm

Due to a fault in the neutron probe after 7/5, the first set of observatios were taken on 23/5. Also, because of maintainance problems with the tensiometers, readings of soil water potential could only be obtained after the week ending on 14/5.

In view of this break in the readings, it was decided to aggregate the observations together. Thus the period starts with a depletion in soil water (Fig. 5.38, Table 5.13) as rainfall decreased. By the end of the period (23/5), the soil was wetter and closer to field capacity as a result of the 34.6mm accumulated rainfall. From matric potentials measured on 14/5 and 21/5, it is possible to visualize the increase in soil water towards the end of the period.

From Fig. 5.38, the beginning of the period was characterized by upward flows of water, as rainfall was low (2mm on 7/5 and 7mm on 14/5). However, by the end of the period the soil was slightly wetter, mainly at the surface (Fig. 5.36). Using the matric potential calculated on 21/5 as a rough guide to infer the direction of the flows, it is suggested that, as the water content was higher at the surface, flows may have occurred in downward direction at least to 25cm depth, while below this depth it is more likely that conditions were stagnant, in the sense that there were no movements of water. Runoff occurred only at the end of the period, in gutters A1, B1 and C1, averaging 1.0mm.

The soil water balance was aggregated to include two periods, from 24/5 to 4/6. Rainfall was 20.2mm, accumulated by 24/5, and caused an increase in the matric potential followed by a subsequent decrease on 4/6 as the soil dried out (Table 5.13); neither runoff nor deep drainage occurred.

From 4 to 11/6, the rainfall accumulated was 10.1mm causing an increase in the soil water potential at 10cm, as can be inferred from Fig. 5.38. Flows were in downward direction to 25cm and no significant movement of water occurred below this depth. In the week ending on 25/6 (following the fortnightly routine of neutron probe readings), the rainfall accumulated was 39.7mm, and the average runoff of 3.2mm was measured in gutters A1, B1 and C1.

Rainfall occurred at the beginning of the first week (11-18/6), and of the 32mm accumulated during this week, 25.5mm fell between 11th (night) to 13th/6 and the rest, 6.5mm, as two events later in the week. In the second week (18-26/6), the rainfall accumulated was 7.5mm distributed as light rain early in the week. In view of this rainfall distribution, it is possible to conclude that runoff occurred in the first week and also to understand the relatively low and similar matric potentials, at 10cm, measured on 18/6 and 25/6.

During this period (12/6 to 25/6), as can be deduced from the tensiometer results, there was no downward movement of water. In fact, it is likely that some water moved upwards to be stored in the soil. This conclusion is reinforced by the soil water balance (Table 5.13) which indicates a small input of water in the profile.

The interval from 26/6 to 9/7 was also considered as one period. Rainfall accumulated was 24.8mm and during this period the average runoff was 0.4mm, collected in gutters B1 and C1. Soil water content decreased close to the surface (Fig. 5.36). Of the 17mm precipitation accumulated in the first week, 14mm was collected between 2/6 and 27/6 with the rest 3mm distributed in three events up to the end of the week. The second week accumulated 7.8mm, sparsely distributed during the week.

Given this rainfall distribution, it is possible to relate the measured runoff to the main rainfall amount at the beginning of the first week. However, as the soil was presumably wet, runoff quantity was low. As a result of the distribution of the rain in the second week, runoff did not occur.

Flows were in a downward direction from the surface to 25cm depth, and in upward direction from 50cm to 25cm.

Rainfall accumulated during the week ending on 16/7 was 22.6mm, increasing the soil water content as shown in Table 5.13. Runoff was 3.0mm collected in gutters A1, B1 and C1. As shown in the matric potential results, the main change occurred at 25cm depth, indicating that water recharging the surface layer infiltrated to 25cm depth.

Movements of water in the soil profile were in downward direction from the surface to 25cm depth. Below this depth the water was immobile.

The differences in the matric potential between the topsoil and subsoil, as has already been observed, controlled the occurrence of runoff.

For the week ending on 23/7, the rainfall accumulated was 31mm, resulting in an increase in the soil water content throughout the entire profile (Fig 5.36). Average runoff was 2.0mm collected in gutters A1, B1, and C1. The gain in soil water content can also be seen from Fig. 5.38 where the matric potentials have increased slightly throughout the soil profile.

During this period, the soil water content increased throughout the whole profile and this occurred during a period of almost uniform matric potential down the profile close to field capacity. However, the amount of runoff did not increase, in fact it decreased slightly in relation to the previous week, supporting the premise that when the soil is wet, at almost uniform matric potential near to field capacity, downward flows within the soil prevail over lateral runoff.

The amount of precipitation measured for the next period, week ending on 30/7, was the highest measured during the summer of 1985 and was 128.7mm. As expected, the runoff collected in this period was also the highest for the whole period of 1985, averaging 11mm. The major runoff quantities were measured on gutters A1, B1 and C1, although a minor quantity occurred in gutter A2.

During this period, the matric potential gradients indicated that infiltration of water into the soil profile would be accelerated. However, the intensity of the precipitation, 70mm in 24 hours, was such that runoff occurred. This again shows that in extreme circumstances the hillslopes may exhibit Horton's oveland flow.

From the water balance it is clear that, despite the occurrence of runoff, a significant quantity of water was lost as deep drainage. Using the hydraulic potential gradient (at 30/7) and the hydraulic conductivity

(35cm/day), it is possible to see that the soil could move a maximum of 213.5mm of water per day, indicating that the estimated deep drainage value (Table 5.13) can be accepted.

This deep drainage was the first significant quantity of the period, occurring much earlierthan during the previous year and gives an idea of the variability in time of the deep drainage process.

The soil dried slightly at the surface as a result of the low rainfall accumulated in the week ending on 6/8, although the lower horizons remained at field capacity from the last reading. Runoff did not occur during this period. Tensiometer readings were not available as they had been removed for test against leaks.

In the week ending on 13/8, 20.0mm of rainfall increased the soil water content, keeping the whole profile close to or at, field capacity. Runoff was only 0.4mm measured in gutters B1 and C1. The matric potentials show the soil to be very close to field capacity and it is possible to deduce (Fig. 5.38) that water moved in a downward direction from the surface to 25cm depth but, below 25cm, there may have been slight movement in upward direction.

The soil water content remains unchanged within the soil profile, close to field capacity, as shown by the matric potential, for the week ending on 20/8. The tensiometers indicate very little change. However, in view of the wet soil conditions, and the similarity with the previous week, it was not surprising that all the precipitation (20mm) entered the soil, explaining the absence of runoff.

The rainfall accumulated in the week ending on 27/8 was 26.5mm and the soil was still close to, or slightly above, field capacity, as can be seen from the tensiometers measurements. Again, no runoff occurred as matric potential gradients encouraged entry of water at soil surface.

Following the sequence of measurements, (Table 5.13), the total rainfall accumulated in the fortnight ending on 10/9, was 46.5mm. Matric potentials indicate that any flow of water would be downwards under the influence of gravity. Runoff did not occur during this period.

The next two week period ended on 24/9, and during this time a considerable amount of rainfall (127mm) was measured (*). Most of this storm occurred between 21st and 22nd/9 and during this 24 hours period, the total rainfall accumulated was 67mm. The principal rainfall events during the 24 hours were:

(1) Two events of 8mm hr^{-1} (duration 1 hour)

(2) Two events of 4mm hr^{-1} (duration 1 hour)

(3) One event of 3.2mm hr^{-1} (duration 2.5 hours)

(4) One event of 3.2mm hr^{-1} (duration 3 hours).

(*) Although precipitation intensity data was not available for the study site, data was available from the Meterological Department at their King'sBuilding site, which can be used to show the intensity of the rainfall events.

As shown above, two heavy (greater than 4mm hr^{-1}) rainfall events occurred during the storm and in contrast with previous reported intense storms, there was a negligible amount of runoff, only 0.15mm, collected in gutters A1 and C1. This low runoff amount was not expected, due to the apparent similarity of the soil water regime on these occasions, in other words a uniform soil water content at or near field capacity. The fact that there was no runoff, may be due to the slightly wetter status of the soil at this time compared to the previous events. Using the given hydraulic conductivity and the potential gradient at 21/9, it is possible to accept the estimated deep drainage amount of 105mm, as the results of the calculation showed that the soil could take up to 101.5mm of water per day.

Matric potentials were measured on 21 and 24 /9, and it is noticeable that there was no change between 10th and 24 /9. However, after the storms ceased, there was a slight decrease in the matric potential by the end of the period. Flows were in downward direction through the profile as can be inferred from Fig. 5.38.

The next group of weeks ended on 8/10. The amount of rainfall was 41.7mm and the soil water content and the matric potentials remainded practically unchanged from the last readings. It is obvious that water content would have been increased by the rainfall events on 2nd and 4th October; however, as the soil was at field capacity, this excess of water was lost as percolation, as can be inferred from Fig. 5.38.

The amount of rainfall decresased to only 5mm in the two week period ending on 22/10, resulting in a decrease in soil water content (Table 5.13).

The potentials measured on 15/10 and 22/10 also show this soil water loss, indicating decreased values in comparison with the previous observations.

From Fig. 5.38, it can be seen that, as the soil was drier on 22/10, flows were in upward direction close to the surface. Below 25cm depth, slight downward movement occurred. It appears that this decrease in water content was partitioned into a slight upward movement to meet the evaporative demand and a small quantity of excess water which drained out of the base of the profile, since lateral runoff did not occur during this period.

The next two week period ended on 5/11 and rainfall had increased to 12.6mm resulting in a slight increase in soil water content (Table 5.13). This increase in soil water is only noticeable in the top layers as can be seen from the matric potentials measured on 29/10 and 5/11. At and below 25cm depth, matric potentials remained practically unchanged.

The potential gradients appear to indicate downward flow from the surface to 25cm depth, and slightly upward from 50cm to 25cm depth. Average runoff was 0.5mm during the period.

The rainfall amount accumulated in the next fortnight (ending on 19/11) of 23.7mm, resulted in an increase in soil water content to cancel out the loss in the previous period. Potentials measured on 12 and 19/11 indicate this increase at both 25cm and 50cm depth. However, the neutron probe indicates that water content increased at the top of the horizons as well. This discrepancy could be due to the inherent variation in soil potentials as measured by the groups of tensiometer in the field.

The direction of the water flow, implied by Fig. 5.38, was slightly down profile until 12/11. However, by 19/11, there appeared to be negligible movement of water.

In the two week period ending on 3/12, the rainfall accumulated was 40.0mm. The neutron probe was not available on the final day of this period, but readings were obtained on 5/12. Unfortunately, by this time the very cold weather affected the tensiometers and they were removed from the study site. Thus data on the matric potentials was only available for the first week from 19 to 26/11.

Considering these restrictions, it is not possible to examine this final period in detail. However, in view of the low evapotranspiration rates at this time of the year and the high rainfall amount (40.0mm), the slight increase in soil water content (Table 5.13) was not surprising. Also, any change in matric potentials would be small and one would expect percolation of water throughout the soil profile. During this period a slight runoff amount, 0.8mm, was detected from gutters A1, B1 and C1.

Discussion

Reviewing the events of the second field season, it is apparent that in wet soil, at or near field capacity during most rainfall events, runoff amounts were essentially low or negligible. This indicates that the matric potential gradient within the soil profile is one of the main control factors of runoff generation. Runoff occurrences in this field season, as with 1984, were concentrated in the period when evaporative demand was high (summer), and this permits one to infer that, in the time interval between rainfall events, matric potential gradients should have developed within the profile. Thus, after a brief rainless period, the top soil layer would be drier than the subsoil and infiltrating water during a rainfall event would first move laterally producing runoff. Subsequently, as the top soil layer was at high soil water content it would rapidly reach potential values above field capacity leading to downward movement and lateral runoff would cease. This permits an understanding of the low runoff amounts observed, although due to the interval between tensiometers readings this assumption is not obvious.

As the soil moisture content increase towards the end of the field season (November), runoff amounts were even lower and the occurrence of runoff became sparse. Again, the matric potentials measured, indicate that flows were controlled by gravity as the zero flux plane disappeared. Also as the evaporative demand was low, a brief period of low rainfall quantity (as for example, from 9/10 to 22/10 and 23/10 to 5/11) was not sufficient to cause any significant soil moisture deficit. This implies that in the subsequent events, water rapidly replenished the entire soil profile, increasing the matric potentials uniformly which again led to drainage.

This behaviour of the soil water is similar to the pattern already described for the previous field season. It also confirms the assumption that it is not necessary for the soil to reach field capacity to generate runoff. In fact it shows the opposite, i.e. when the soil is at field capacity and receives excess water, lateral runoff tends to decrease or cease.

Considering the occurrence of deep drainage, the picture for this field season is also similar to 1984. Deep drainage occurs when the evaporative demand is low, giving an opportunity for the replenishment of soil macro pores. This means that although the 'summer' of 1985 was wetter than 1984, water was retained in the small pores of the soil. However, in the event of an excessive amount of rain (as on 30/7) 'summer percolation' occurred, leading to the loss of a large quantity of water through the base of the profile. It is worth mentioning that before this 'summer percolation' event, four rainfall events greater than 20mm had been measured. However, although in two consecutive weeks there was a gain in the soil water, none of the events generated significant deep drainage. It was the rainfall event with 70mm in 24 hours (during a time of high evaporative demand) which replenished the soil macro pores sufficiently to release water down the soil profile. The quantity of water lost as deep drainage in one week was 101mm and the quantity lost as runoff only 11mm. Continuously wet soil over much of the 1985 field season, resulted in continuous deep drainage.

After the high deep drainage event of 30/7, precipitation in the next week (31 to 6/8) decreased (9.0mm) but in the subsequent weeks of August 1985, although the rainfall amounts were not high, rainfall occurred on 29 days, keeping the soil permanently wet. This is shown by significant amounts of deep drainage throughout August. As the rainfall continued through September at increased amounts, a second major deep drainage event occurred after 127mm of rainfall accumulated in two weeks (11/9 to 24/9). As was shown earlier, 67mm of rainfall occurred in 24 hours and it is interpreted here that the major part of the 105.3mm was lost through the base of the profile. The amount of runoff compared with the previous event (30/7), was even lower supporting the hypothesis that runoff amounts are low when the soil is uniformly wet.

Chapter Six

Conclusions

The work reported in this thesis described the basic flow processes in a freely drained brown earth soil covered with improved grassland in a rectilinear hillslope segment, by means of three replicate plots and a further unrestricted control plot. Emphasis was placed on measurements of accuracy of the data and also on the possible disturbances to soil water behaviour caused by the construction of a trench. From the results and discussion in the previous chapter, the following groups of conclusions can be drawn.

1. Runoff

a. The evidence from the research site showed that it was not necessary for the soil to reach field capacity in order to generate runoff, indeed, nearly all the observed runoff events occurred in conditions of soil moisture deficit.

b. Further, runoff occurred at low rainfall amounts and intensities. This implies that soil water potential gradient is one of the most important factors in the interpretation of the runoff.

c. Low runoff quantities were recorded at the research site. This is interpreted firstly, because runoff events occur when soil is at moisture deficit in the 'summer periods' when rainfall amounts are usually low. Secondly, because in the wet periods (autumn-winter) although rainfall is usually abundant, the soil is thoroughly soaked at high and uniform matric potentials, which leads to a predominance of deep drainage over runoff.

d. Runoff events and amounts, over the hillslope segment studied, may be predicted with a reasonable accuracy by the use of small plots replicates.

2. Deep drainage

a. Deep drainage was not measured directly, but can be derived from analysis of the soil water balance.

b. Deep drainage appeared to be one of the principal 'sinks' for water arriving on the experimental plots and occurred whenever the soil profile was wet and contained uniform matric potentials.

3. Field experimental method

a. Replication of plots and the cross-checking permitted a satisfactory explanation for the apportionment of precipitation incident upon the experimental site.

b. The control plot was useful only in the checking of the temporal pattern of runoff from the confined plots, despite the fact that its data could not be used quantitatively.

c. The construction of a trench (measuring 11.0m X 1.60m X 1.0m) did not appear to disturb the soil water regime over the two field seasons examined.

d. The full range of measurements was required in order to obtain satisfactory data for assessing the soil water balance accurately. This included methods for measuring runoff (from artificial plots), soil water potential (using mercury tensiometers) and soil water content (using a neutron probe). However, it would have been helpful to have had automatic and continuous records of runoff and soil water potential in order to monitor more accurately the soil water conditions in which runoff occured.

4. Field model

The models proposed by Hewlett or Horton do not adequately explain the disposition of the water within the soil profiles investigated. It appears that Burns' model is more appropriate in interpreting the observed soil water regime.

Appendix A

Methods of soil analysis

1. Particle size by pipette sampling for silt and clay and sieving for fine and coarse sands (Black, 1965).

2. Exchangeable calcium, magnesium, potassium and sodium by leaching soil with 1N ammonium acetate buffered at pH 7.0 (Allen et.al, 1974); calcium and magnesium determined in the leachate by atomic absorption method; potassium and sodium determined by flame emission method.

3. Field capacity by means of porous plate assembly at tension of 50cm of water (Department of Agriculture, 1983).

4. Wilting point by means of a pressure tank at a pressure of 225 psi (Department of Agriculture, 1983).

5. pH with glass electrode pH meter in distilled water and also in 0.01M calcium chloride at soil to liquid ratio 1:2.5 (Black, 1965).

6. Organic carbon by means of a 'EEL' photoelectric colorimeter (Department of Geography).

Appendix B

Rainfall and runoff measured in plots A, B, C and D

date	rainfall mm	runoff mm A	B	C	D
1984					
8/5	5.5	0.0	3.4	0.0	0.0
15/5	0.5	0.0	0.0	0.0	0.0
22/5	12.9	0.8	7.7	5.7	45.0
29/5	28.1	0.6	4.5	4.8	0.8
5/6	28.7	0.4	7.1	6.3	1.7
12/6	19.2	0.3	4.0	4.2	3.9
19/6	0.7	0.0	0.0	0.0	0.0
26/6	4.6	0.6	1.2	0.8	4.5
3/7	1.5	0.0	0.0	0.0	0.0
10/7	2.0	0.0	0.0	0.0	0.0
17/7	6.0	0.9	1.2	1.0	1.9
24/7	0.0	0.0	0.0	0.0	0.0
31/7	18.7	6.1	7.4	4.9	0.6
7/8	17.2	0.2	1.0	1.7	0.1
14/8	2.0	0.0	0.0	0.0	0.0
21/8	0.4	0.0	0.0	0.0	0.0
28/8	1.5	0.0	0.0	0.0	0.0
4/9	34.3	6.6	6.3	9.5	17.0
11/9	4.6	0.0	0.0	0.0	0.0
18/9	18.6	0.4	2.0	2.9	1.3
25/9	33.8	10.3	6.7	9.9	33.8
2/10	9.7	0.0	0.0	0.0	0.0
9/10	4.0	0.0	0.0	0.0	0.0
16/10	7.8	0.0	0.0	0.0	0.0
23/10	26.5	1.56	1.8	5.7	6.8
30/10	31.0	5.7	2.5	6.1	3.9
6/11	113.0	36.0	21.2	31.2	118.0
13/11	44.8	3.4	0.8	6.46	1.8
20/11	19.5	0.0	0.0	0.0	0.0

28/11	31.6	5.7	1.87	6.49	5.4
4/12	18.0	0.0	0.0	0.0	0.0
11/12	9.4	0.0	0.0	0.0	0.0
18/12	4.5	0.0	0.0	0.0	0.0
24/12	19.5	0.0	0.0	0.0	0.0
31/12	6.2	0.0	0.0	0.0	0.0
1985					
29/1	10.1	11.4	7.4	10.4	4.7
5/2	10.9	0.1	1.2	1.4	0.6
21/2	33.9	5.1	4.9	1.6	2.2
26/2	1.5	0.0	0.0	0.0	0.0
5/3	10.0	0.09	0.1	0.1	0.1
12/3	5.5	0.0	0.0	0.0	0.0
19/3	5.3	0.0	0.0	0.0	0.0
26/3	23.4	0.0	0.0	0.0	0.0
2/4	52.5	0.0	0.0	0.0	0.0
9/4	37.6	0.0	0.0	0.0	0.0
16/4	25.0	0.0	0.0	0.0	0.0
23/4	8.1	0.0	0.0	0.0	0.0
30/4	7.1	0.0	0.0	0.0	0.0
7/5	2.0	0.0	0.0	0.0	0.0
14/5	7.0	0.0	0.0	0.0	0.0
21/5	27.6	0.66	0.66	1.92	0.1
28/5	20.2	0.0	0.0	0.0	0.0
4/6	0.0	0.0	0.0	0.0	0.0
11/6	10.1	0.0	0.0	0.0	0.0
18/6	33.5	0.6	1.62	7.4	0.1
25/6	6.2	0.0	0.0	0.0	0.0
2/7	17.0	0.0	0.0	1.2	0.0
9/7	7.8	0.0	0.0	0.0	0.0
16/7	22.6	2.2	1.6	4.83	0.0
23/7	31.0	0.9	0.6	4.93	0.0
30/7	128.7	5.2	3.1	24.3	66.4
6/8	9.0	0.0	0.0	0.0	0.0
13/8	20.0	0.0	0.4	0.61	0.0
20/8	20.0	0.0	0.0	0.0	0.0
27/8	26.5	0.0	0.0	0.12	0.05
3/9	26.5	0.0	0.0	0.0	0.0
10/9	20.0	0.0	0.0	0.0	0.0
17/9	6.0	0.0	0.0	0.0	0.0
24/9	121.0	0.2	0.0	0.12	0.3
1/10	18.7	0.0	0.0	0.0	0.0
8/10	23.0	0.0	0.0	0.0	0.0
15/10	4.0	0.0	0.0	0.0	0.03
22/10	1.0	0.0	0.0	0.0	0.0
29/10	0.0	0.0	0.0	0.0	0.0
5/11	12.5	0.4	0.29	0.88	0.2
12/11	15.2	0.0	0.0	0.0	0.0
19/11	8.5	0.0	0.0	0.0	0.0
26/11	9.5	0.0	0.0	0.0	0.0
3/12	30.4	0.12	0.32	1.8	0.2

Appendix C

Average matric potentials and standard deviation for three depths

FREE FACE

date	10cm ψ_m	s.d.	25cm ψ_m	s.d.	50cm ψ_m	s.d.
3/7	426.6	133.0	376.6	64.9	107.1	78.1
10/7	665.7	63.8	336.8	126.0	113.0	66.5
14.8	405.0	49.6	274.6	102.2	453.9	108.8
21/8	467.7	124.1	98.4	28.5	104.7	38.6
28/8	539.0	82.9	189.8	85.8	166.9	90.7
4/9	253.0	131.9	90.0	8.3	127.3	58.2
11/9	702.5	84.8	96.7	20.9	100.5	54.0
19/9	194.3	44.4	233.0	63.7	271.8	112.9
25/9	275.4	115.9	117.5	32.0	89.1	35.0
2/10	284.6	88.0	94.7	18.6	86.8	25.5
9/10	412.0	49.5	122.2	35.8	218.8	68.6
16/10	284.3	72.0	129.2	34.6	188.9	65.0
23/10	106.3	15.0	73.6	17.9	85.3	11.2
25/10	105.9	12.4	90.9	8.6	82.7	3.9
30/10	120.2	27.1	95.7	9.1	81.7	5.1
31/10	97.7	10.0	99.7	5.0	87.0	6.1
1/11	101.4	15.5	91.2	7.4	90.6	7.7
4/11	79.4	5.4	83.1	5.7	81.5	5.1
6/11	105.6	22.7	89.9	13.2	108.7	13.0
9/11	92.0	11.1	71.1	7.6	84.3	6.8
10/11	87.0	8.7	74.7	7.6	82.9	5.9
13/11	100.2	13.7	80.3	10.6	90.4	6.9
20/11	94.6	4.3	96.1	3.1	86.6	1.6
28/11	85.3	3.2	86.2	4.5	80.8	2.6
30/11	107.1	9.7	97.7	6.8	88.3	3.1
5/12	90.1	5.0	89.8	4.7	90.1	6.4
11/12	100.0	6.8	100.0	6.1	95.4	4.7
18.12	133.3	30.0	100.0	14.5	82.2	6.3

24/12	80.1	3.1	80.5	4.3	80.5	4.0
31/12	89.8	10.3	89.6	3.7	79.8	5.9

UPSLOPE

date	10cm ψ_m	s.d.	20cm ψ_m	s.d.	50cm ψ_m	
3/7	438.6	*	148.1	*	112.1	*
10/7	329.6	*	105.8	*	131.8	*
14/8	194.9	173.1	349.4	55.3	486.0	104.1
21/8	matric potential beyond range tensiometers					
28/8	matric potential beyond range tensiometers					
4/9	matric potential beyond range tensiometers					
11/9	matric potential beyond range tensiometers					
19/9	186.2	113.9	269.1	27.1	305.4	114.2
25/9	125.9	25.8	125.9	17.0	122.0	16.4
2/10	200.7	67.2	168.8	23.7	144.5	22.1
9/10	183.4	27.6	280.2	19.0	265.0	56.5
16/10	162.2	62.0	354.8	62.5	201.8	39.3
23/10	66.8	3.9	75.0	8.2	68.0	2.1
25/10	56.2	6.8	67.6	13.3	58.2	1.3
30/10	66.0	5.1	67.6	12.3	46.2	14.3
31/10	83.6	14.3	85.6	2.7	57.8	3.1
1/11	92.7	13.6	88.1	13.0	66.4	1.8
4/11	79.4	13.6	85.6	11.4	62.3	2.2
6/11	138.8	25.5	93.3	13.8	83.1	6.7
9/11	82.6	11.2	72.8	11.5	62.3	1.4
10/11	82.2	11.8	72.8	9.0	59.5	0.2
13/11	98.2	14.1	78.5	20.8	71.6	5.2
20/11	72.8	19.4	83.1	13.5	58.8	6.8
28/11	69.1	17.3	67.6	10.1	56.5	7.5
30/11	77.6	22.1	77.1	14.6	53.0	10.5
5/12	90.1	5.7	85.1	8.5	72.8	11.0
11/12	105.3	7.0	93.3	11.7	75.4	9.2
12/12	73.7	11.3	81.7	18.3	66.0	7.9
24/12	67.2	5.0	67.9	1.6	54.9	11.2
31/12	39.1	8.2	53.3	3.6	56.2	4.2

* no error calculated less than 3 tensiometers operating

FREE FACE

date	10cm		25cm		50cm	
	ψ_m	s.d.	ψ_m	s.d.	ψ_m	s.d.
14/5	293.4	87.2	241.2	23.6	138.5	48.5
21/5	154.8	43.7	105.0	9.0	107.1	14.7
28/5	131.4	25.1	114.1	6.5	94.6	8.1
4/6	165.4	59.5	168.3	37.3	119.5	19.3
11/6	138.0	48.1	233.0	67.1	186.2	72.0
18/6	295.1	99.6	153.1	16.8	118.8	23.0
25/6	282.6	98.1	211.9	25.9	114.5	27.7
2/7	162.1	56.4	203.0	35.7	130.3	38.6
9/7	110.5	36.3	201.8	55.8	101.7	27.6
16/7	97.1	30.3	117.1	27.8	91.4	22.1
23/7	88.8	25.1	118.8	22.9	76.1	9.0
30/7	82.9	25.1	74.1	6.2	67.6	8.5
13/8	67.2	7.7	87.1	7.1	63.3	12.0
20/8	61.6	9.8	92.9	18.9	64.3	15.4
27/8	58.0	8.0	79.2	10.9	49.3	16.8
10/9	83.1	16.1	79.6	13.7	78.2	2.6
17/9	99.1	17.9	106.8	11.7	53.0	24.5
21/9	75.8	11.5	60.9	12.8	47.5	22.7
24/9	113.9	3.0	101.1	4.2	80.3	6.7
1/10	101.7	6.4	85.1	6.8	76.7	4.8
8/10	105.0	11.5	100.0	5.6	77.8	6.4
15/10	116.4	15.5	111.2	9.9	86.0	8.1
22/10	155.3	23.5	133.7	14.4	92.5	10.9
29/10	129.1	27.4	142.8	20.5	94.1	12.3
5/11	100.8	21.3	147.0	23.6	100.8	13.8
12/10	194.7	23.0	118.8	22.0	109.3	21.6
19/11	112.2	13.2	105.9	9.3	80.2	7.3
46/11	46.7	10.7	73.0	6.4	60.7	6.0

UPSLOPE

date	10cm		20cm		50cm	
	ψ_m	s.d.	ψ_m	s.d.	ψ_m	s.d.
14/5	206.3	43.1	155.7	46.4	120.9	19.7
21/5	89.1	10.6	120.9	23.3	77.6	10.9
28/5	95.4	11.1	81.2	17.6	38.0	24.9
4/6	138.5	*	68.1	3.6	50.1	25.1
11/6	125.9	84.6	64.5	2.2	84.4	42.5
18/6	81.2	27.2	96.9	36.2	90.1	13.4
25/6	84.4	39.0	100.0	42.3	33.5	28.8
2/7	55.5	3.6	51.2	5.3	173.7	31.9

9/7	197.2	87.2	147.9	109.2	68.3	32.5
16/7	120.9	38.1	114.8	56.8	70.3	27.3
23/7	77.0	22.4	74.1	8.5	47.8	12.4
30/7	59.5	13.7	62.0	5.4	42.6	13.1
13/8	57.8	11.5	59.9	4.5	49.2	9.9
20/8	62.1	24.5	60.6	4.7	38.9	7.6
27/8	66.0	11.5	57.2	5.9	45.7	11.9
10/9	49.8	7.9	60.9	2.5	46.7	13.1
17/9	58.4	2.0	67.6	3.1	50.1	15.2
21/9	45.9	5.2	56.8	6.2	38.2	10.6
24/9	61.6	5.3	64.1	1.6	47.8	15.2
1/10	57.9	0.4	55.9	5.5	43.4	13.9
8/10	78.5	6.2	81.2	14.0	43.6	14.6
15/10	53.7	9.0	86.5	17.2	45.1	16.9
22/10	56.5	7.3	67.6	6.8	48.6	18.2
29/10	54.3	6.3	90.6	16.8	51.8	20.4
5/11	57.5	3.3	72.0	9.3	63.0	23.3
12/11	53.3	3.5	58.2	6.8	33.6	9.5
19/11	53.7	*	56.5	3.9	40.4	2.4
26/11	57.9	*	62.3	4.7	36.3	7.2

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